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THE EFFECTS OF SEWAGE SLUDGE DEPOSITION ON ECOSYSTEM CARBON EXCHANGE PROCESSES: POSSIBILITIES OF MODEL-BASED ASSESSMENTS

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Abstract: The growing interest in the concept of the circular economy calls for methodological development in several fields of environmental research and management. Life cycle analysis needs an integrated accounting of different production and waste treatment processes, which is the case also for carbon footprint calculations. If the aim is the assessment of sewage sludge utilization, model-based approaches are needed, because of the high number and the complex character of the related ecosystem processes. Our study gives a short overview of the actual background of this field, together with raising some methodological aspects of the relevant model development efforts. Owing to the detailed technical regulations, the industrial parts of the process can be relatively easily modeled, while the agricultural deposition of sewage sludge needs the use of the toolset of ecophysiological modeling. The main methodological aspects of integrated (technical-ecological) modeling are the following. As the agricultural management practices strongly affect the greenhouse gas exchange processes, models are preferred that represent these aspects in the parameterization. Spatially distributed models are suitable for a number of related decision-making processes. In general, the methodological elements of simplified performance assessments of other relevant fields have to be taken into consideration, together with the practical experiences of similar complex modeling systems (e.g. agricultural production and greenhouse gas).

Keywords: life cycle approach, sewage sludge deposition, ecosystem carbon exchange, ecophysiological model

1. INTRODUCTION

Contemporary environmental problems, especially global climate change, call for integrated efforts to mitigate the effects and to achieve sustainable solutions in every economic sector. One reasons for this is the complexity of the affected geoecological systems: the behavior of different ecosystems in situations such as rising temperatures or different agricultural management interventions is not always known. On the other side, almost every part of the agricultural or industrial processes has some effects on the greenhouse gas balance. These facts have led to the emergence of the concept of the circular economy, and the need for life cycle analyses as a type of environmental assessment tool, and in a wider sense, as a new approach in environmental management. The circular economy describes an economic system that is based on business models which replace the "end-of-life" concept with reducing, reusing, recycling, and recovering materials in production/distribution and consumption processes, operating on different scales [1]. One method for its practical implementation is the life cycle assessment, which is an overall environmental analysis of products and services, through the life cycle from raw material extraction to waste treatment.

These developments have high relevance in the field of sewage sludge utilization. It can be considered a leading implementation of the concept, as due to the general availability of municipal wastewater treatment, millions of metric tons of dry matter are generated every year in the European Union [2]. Despite the strict regulations of the countries, the usage of sewage sludge in agriculture and for energy generation has an increasingly important role in the relevant sectors. Following this, there is a need for integrated experimental analyses of the different utilization possibilities, in a circular economy context and with the aim to be as applicable to other places and similar cases as possible [3].

A life cycle analysis of sewage sludge utilization focuses on the agricultural usage and the carbon footprint of the process, but the effects of the deposition on the carbon exchange processes of the agroecosystem also have to be investigated. For these types of assessments, model-based approaches can have a leading role. There are several reasons and cases in environmental sciences and applications where modeling provides a good solution, and sometimes the only solution. The complexity of the analyzed ecological systems (or their connections with industrial processes) might call for a simplified description, which is one of the main added values of models of complex systems [4]. Moreover, in the case of the development of such methods, which are intended to be widely usable in practice (in engineering, impact assessments, etc.), automated or mostly automated processes are advantageous, possibly with user-friendly software solutions. The multiscale character of environmental processes can also be handled in modeling approaches [5]. Therefore, we consider it important to develop model-based assessment methods to help carbon footprint estimations of sewage sludge disposal and related industrial and agricultural activities. Based on that, our aim is to provide a short review of the literature of modeling possibilities of this chain of activities, including the agricultural utilization. Then we raise and discuss some points on model choice and other methodological aspects, focusing on the sludge disposal's secondary effects on biogeochemical processes of agroecosystems. Our work is part of a wider project aiming at the holistic assessment of sustainability aspects of sewage sludge utilization. This paper serves as supporting material for a detailed, site-specific model-based assessment, based on the methodological background presented here.

2. MODELLING GREENHOUSE GAS FLUXES IN WASTEWATER AND SEWAGE SLUDGE TREATMENT PROCESSES AND AGROECOSYSTEMS

As the value chain of wastewater management consist mostly of carefully planned and regulated technical processes, calculations related to external effects (like greenhouse gas emissions) might be considered easier to make. It can be said that following the technical developments and the relevant policy initiatives, the modeling of the carbon footprint in this case has gone through the classical stages of model development. The first known quantitative connections make the development of empirical models and equation sets possible. One example for that is the set of IPCC Guidelines [6], which play an important role in the development of the scientific/technical background and the practical applications in this field. Later, based on the results of further research and experiences from practical applications, more complex process-based models have been developed [7], sometimes with user-friendly software implementations. The GestaBoues Tool (developed in France) takes into account direct, indirect and avoided emissions [8]. The BEAM calculator tool (Biosolids Emissions Assessment Model – (developed for Canadian circumstances) uses spreadsheets, which are suitable for general use by many municipalities [9]. And, following the widespread use and the popularity of life cycle assessments, a number of targeted software tools have been introduced for interested companies of different sectors, most of which are suitable for investigating the sewage sludge processing and end use (e.g. SimaPro, GaBi). The growing amount of modeling experience and results form a foundation for comparative assessments of relevant management alternatives [10]. However, large discrepancies could be found in the selection of the environmental emissions to be included in the life cycle assessments, or how they were estimated in the analysis [11]. This is especially true for the agricultural use of sewage sludge, as it is connected to complex agroecosystems. For them, the effects of different management options are not clarified totally, and the functioning of the system needs its own specific modeling framework.

Because of the above-mentioned aspects, there are several models of different subtargets and model complexities, which aim at assessing the greenhouse gas fluxes of different agricultural forms, under different management practices and different climatic circumstances. Agroecosystems are relatively well-studied because of the need for productivity estimations. But it has also been true for this field that the development of targeted models and software tools many times needed some new, primary (mostly field-based) results to add some missing parts. The challenges of modeling carbon exchange processes lie in the multi-domain character of the system. The results on the core process, the primary production of vegetation, are modified by several factors: the autotrophic and heterotrophic respiration serve as a source of carbon output. There is also the need for a clear distinction between the carbon input or output processes of the soil and the total ecosystem, and for the calculation of the effects of different agricultural management interventions. The subprocesses, which are ideally incorporated in the greenhouse gas balance models of ecosystems, can be seen in the architecture of the Biome-BGC model, which will be discussed later *(Figure 1)*.

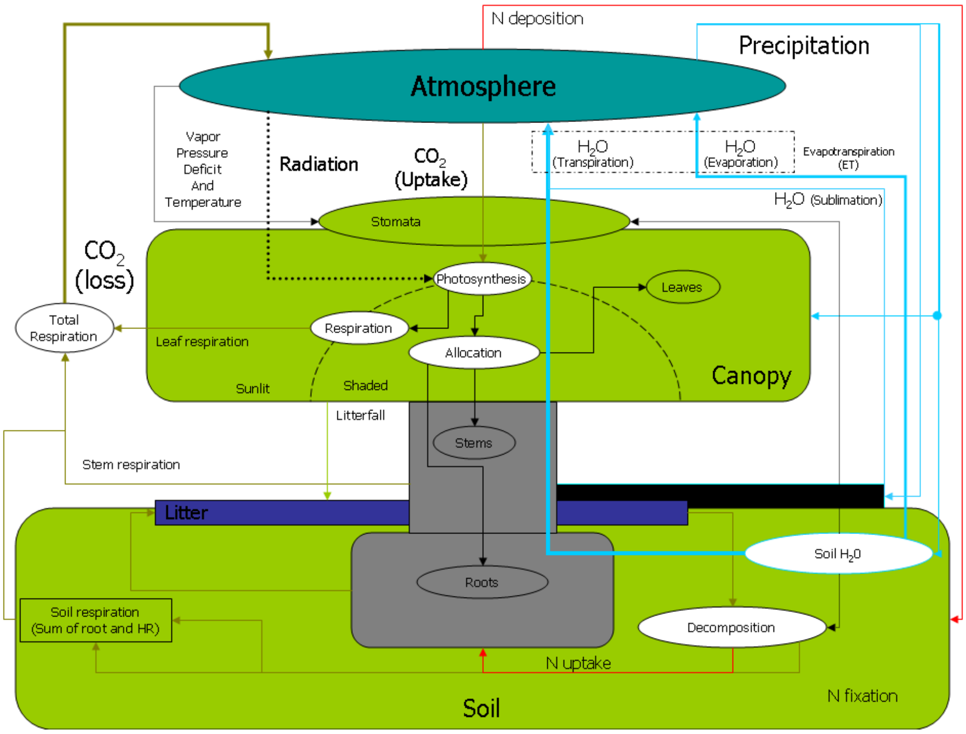

Figure 1

The structure of the Biome-BGC model [12]

Following the requirements above, there are a number of models that enable the detailed description of ecosystems and the assessments of different management (or even climate change) scenarios.

One of the first tools was the CENTURY model, which had been developed from the 1980s, and was implemented in FORTRAN language. It was able to simulate the dynamics of carbon, nitrogen, phosphorus and sulfur for different plant-soil systems (grassland systems, agricultural crop systems, forest systems, and savanna systems). The original version of the model runs in a monthly time step [13]. The improvement of the CENTURY model (e.g. for achieving better temporal resolution) resulted in the introduction of the DayCent model. This tool works based on daily meteorological data and provides daily outputs on fluxes of N gases and CO_2, together with net primary production and other ecosystem parameters [14].

The DNDC model was developed originally for quantifying carbon sequestration and emissions of nitrous oxide, nitrogen and carbon dioxide from agricultural soils in the USA, then was adapted to several other ecosystems and scenarios. Its main advantages are those related to usability: the user-friendly interface and the in-built library of default settings for several crops and soil types [15].

Another widely used, integrated ecosystem model is the Biome-BGC [12], which is point-based and works on a daily basis as well. It was introduced as an extension and generalization of the Forest-BGC model, dating back to the 1980s [16]. A huge advantage of the model is that it has been almost constantly developed and corrected until today, nowadays in the form of a modified model system: the Biome-BGC MuSo [17]. The latter abbreviation refers to the Multilayer Soil Module, which enables a more exact simulation of management interventions, which is especially important in the case of agricultural ecosystems. Similarly to most of the other similar tools, it works with the main model pools of leaf, fine root, fruit, soft stem, live wood, dead wood, coarse root, soil and litter [18].

Besides the above-mentioned tools, there are also some other modeling possibilities; for a comparison see e.g. Campbell and Paustian [19].

3. Some aspects of model selection and application for impact assessment of sewage sludge effects on ecosys-tem carbon fluxes

Although there are a number of easily available and potentially usable models to serve an integrated carbon footprint analysis of the land disposal of sewage sludge, there are some factors that should be taken into consideration in the modeling choice. As the intervention is characterized by a huge amount of additional organic matter input with a special chemical composition, the capability of detailed description of management actions (with a complex assessment of soil processes, especially fertilization) might be important. When croplands are in the focus of investigations, the multi-layer characterization of soils can highly improve model accuracy.

When models or results of models for distinct fields are to be somehow connected or integrated (like in this case with the industrial and ecosystem modeling part), the detailed and public documentation of the relevant elements is crucial. In the recent years, following the growing interest in sustainability assessments of different industrial or other economic activities, there is a need for generally usable targeted platforms. The development of such types of toolsets can be delivered through synthesizing relevant measurement and modeling results, or an expert-based development of simplified performance assessment tools [20], [21]. This systematic process may need to build on some elements of existing expert models. E.g. the AgroMo modelling framework is intended to integrate biogeochemcial and crop modelling to enable a holistic assessment of e.g. climate change effects [22]. In our opinion, some kind of similar integrated modeling system for wastewater treatment would highly improve the effectiveness of relevant decision-making processes. A related aspect is the open source availability of the referring software codes, which can help such modeling efforts very much.

The possibility of spatial extension of the model is definitely an advantage from this point of view, but it is also true that the current GIS capabilities and calculation capacities enable future improvement of models in this direction.

At last, the sequestration and storage of carbon by different types of vegetation is treated as an important ecosystem service, and has a central role in international climate mitigation and biodiversity policies. As such, it can be valued also in monetary terms. This can also be the case for the industrial modeling part, which gives the possibility of an integrated economic assessment, e.g. with a cost-benefit analysis, which may improve the usability of modeling results in different practical applications.

In summary, the integrated modeling of the carbon footprint of the agricultural use of sewage sludge is feasible. The model development efforts needed for that could give usable methodological experience to other environmental management fields, because there is a constantly growing need for impact assessments with a life-cycle approach.

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