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A Strategy for Describing the Biosphere at Candidate Sites for Repositories of Nuclear Waste: Linking Ecosystem and Landscape Modeling

To provide information necessary for a license application for a deep repository for spent nuclear fuel, the Swedish Nuclear Fuel and Waste Management Co. has started site investigations at two sites in Sweden. In this paper, we present a strategy to integrate site-specific ecosystem data into spatially explicit models needed for safety assessment studies and the environmental impact assessment. The site-specific description of ecosystems is developed by building discipline-specific models from primary data and by identifying interactions and stocks and flows of matter among functional units at the sites. The conceptual model is a helpful initial tool for defining properties needed to quantify system processes, which may reveal new interfaces between disciplines, providing a variety of new opportunities to enhance the understanding of the linkages between ecosystem characteristics and the functional properties of landscapes. This type of integrated ecosystem-landscape characterization model has an important role in forming the implementation of a safety assessment for a deep repository.

INTRODUCTION

Nuclear energy is commonly used in many countries all over the world, and in Sweden 50% of produced electricity comes from nuclear power plants (1). One major issue for countries running nuclear power plants is to find an environmentally safe way to dispose of radioactive spent nuclear fuel. Reprocessing, transmutation, monitored storage and emplacement in a deep repository are some examples of proposed approaches. In Sweden, the Swedish Nuclear Fuel and Waste Management Co. (SKB) is assigned by the government to investigate the possibilities for safe management of spent nuclear fuel. During the last few decades, SKB has focused on a deep repository for spent nuclear fuel (Fig. 1), and has accordingly evaluated a number of possible sites, investigated how to construct a repository and analyzed the risks of a potential future release from such a facility (2). At present, SKB is undertaking site investigations and characterizations at two different locations on the south-eastern coast of Sweden, in the Forsmark and the Simpevarp areas (Fig. 2), with the objective of siting a repository for spent nuclear fuel. An important part of these investigations is to develop a site-descriptive model based on site-specific data and its regional setting, covering both the current state of the geosphere, the biosphere and human land use, as well as processes affecting their long-term development. The site description is needed to: a) underpin a safety assessment describing different scenarios and consequences if radionuclides are released from the repository (3); b) detect ecosystem changes caused by the construction of a repository; and c) establish a baseline for detecting long-term effects of the repository.

To achieve a site-specific description of the biosphere at a proposed location for a deep repository, a thorough investigation of the different functional entities (e.g. primary producers), and their properties (e.g. primary production), in the ecosystems is needed. The characterization of the biosphere can primarily be made by identifying and describing important properties in different surface ecosystems, e.g. properties of hydrology and climate (4), Quaternary deposits (5), soils (6), chemistry (7) and vegetation (5), but also current and historical land use, as these are factors that affect today's biosphere (8). Functions and processes other than those studied in the context of natural science, e.g. economic prerequisites, social structures, and cultural heritage, are being increasingly recognized as integral features in landscape modeling, and are thus important to consider when analyzing landscape change (e.g. 9, 10, 11). In the present study, data concerning human whereabouts, both currently and historically (12) are included in the discipline-specific models, as well as in the integrated spatially-distributed ecosystem model (13). This ecosystem model will also be used in dose modeling and assessments of nuclear release (14), where transport and accumulation of radionuclides will be modeled by quantifying biogeochemical pathways of the transport, transformation and recycling of organic matter. The model is therefore also built to quantify processes affecting, for example, turnover of organic matter in catchment areas. By placing the emphasis on the fluxes of matter, the ecological and physical

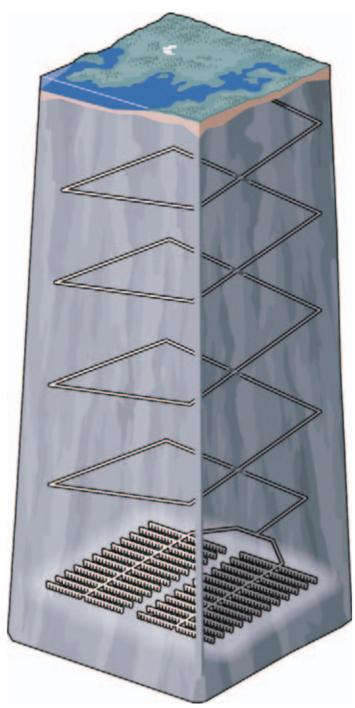

Figure 1. A generalized model of a repository at approximately 500 meters depth in the bedrock.

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constraints on a system can be shown to reduce the potential range of future states of the ecosystem, hence reducing uncertainties in estimating radionuclide flow and in turn radiological consequences to humans and the environment (15). In a radionuclide release scenario, in which hydrologically-driven dispersal may be fundamental, it is important to use a modeling approach that is not limited to single ecosystems, but includes the whole landscape.

With a landscape approach, based on spatially-distributed data and spatial descriptive models, it is possible to understand the causes and consequences of spatial heterogeneity and how the heterogeneity varies both with scale and with the influence of management on natural and human-dominated landscapes (16). Moreover, landscape ecological approaches are not limited to land, but can also be applied to aquatic and marine ecosystems (e.g. 17, 18). Until now, the interface between ecosystem and landscape ecology has not been sufficiently developed. Ecosystem ecology has so far largely considered fluxes of matter and energy in the absence of a spatial context, and landscape ecology has given little consideration to ecosystem processes. However, in some studies, the role of position in the landscape has been elucidated (19), and a meta-ecosystem framework has been developed by extending meta-population models, which are spatially explicit, to represent fluxes of matter or energy (20). Moreover, the regional variation in a variety of stocks and processes (soil organic matter or carbon, denitrification, and net nitrogen mineralization rates) has been explored (e.g. 21, 22). The importance of transfers among patches and habitats in a landscape for the long-term sustainability of ecosystems has also been acknowledged (23, 24). Simulation models, ranging from simple representations (e.g. 25) to complex, process-based spatial models (e.g. 26), have also been employed to identify the aspects of spatial configuration that could enhance or suppress lateral fluxes of matter.

The aim of this paper is to present a strategy for how to interconnect and model surface ecosystems to describe functions and processes at a proposed site for a deep repository for spent nuclear fuel. The paper also functions as a broad introduction to this special issue (Ambio 35 (8), 2006), in which the following ten papers give details of the strategy adopted and the modeling approaches used. The strategy is presented stepwise. First, there is the determination of ecosystem properties and function; second, the development of the framework for the spatially-distributed surface system models; and finally, how the different ecosystem properties are interconnected. The strategy is illustrated by selected interim results, whereas other results are presented in the associated papers in this issue. In addition, we also discuss implications for the safety assessment and dose modeling, and advantages and disadvantages of this kind of ecosystem modeling in a long-term, i.e. longer than 1000 years, perspective.

STRATEGY DESCRIPTION AND INTERIM RESULTS

To study the fluxes of matter within surface systems, the biosphere at the site was divided into different ecosystems that could be interconnected in a landscape model (Fig. 3 in Box 1). The ecosystems were allowed to have different spatial extensions and properties, and each system can be regarded as a stand-alone element with an intrinsic turnover of matter and well-defined interfaces across which exchanges of matter occur with other systems. The two main categories of ecosystem, aquatic and terrestrial, are further subdivided into a number of ecosystem types. Aquatic ecosystems include marine systems, lakes and running water, and terrestrial systems include agricultural land, mire and forest. The radionuclide pathway, described in Box 1, is one of many scenarios that may become

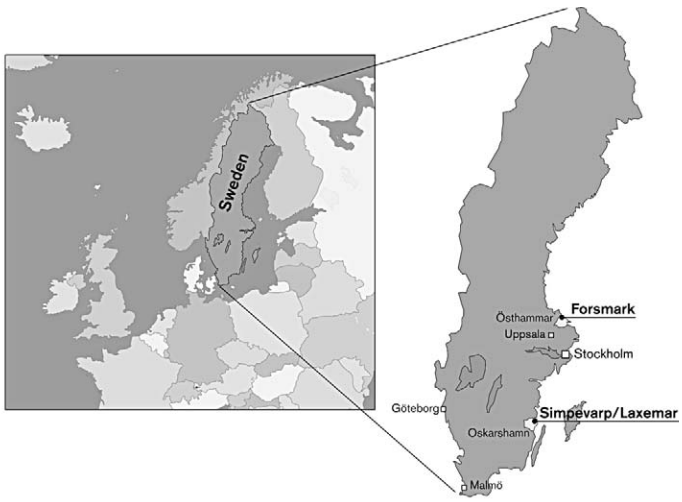

Figure 2. Location of the two sites Simpevarp/Laxemar (Oskarshamn municipality) and Forsmark (Östhammar municipality) where ongoing site investigations have been conducted by SKB since 2002.

reality if a release of radionuclides occurs from a deep repository. To describe the whole site at different spatial and temporal scales we need an array of discipline-specific descriptions and models (5). In this special issue, Ambio 35 (8) (2006), some of these descriptions and models are presented in individual papers: hydrological modeling, pp. 425–434 (27); water exchange and radionuclide transport in a coastal region, pp. 435–447 (28); human activities and land use, pp. 505–512 (12): carbon turnover in terrestrial ecosystems, pp. 448–458 (29); terrestrial carbon budgets, pp. 459–468 (30); carbon fluxes in a lake, pp. 469–483 (31, 32); carbon fluxes in a coastal ecosystem, pp. 484–495 (33); modeling linked ecosystems, pp. 496–504 (13); and modeling radionuclide distribution, pp. 513–523 (14).

Model Development

The development of a spatial model for the surface system can be described in the following four steps (Fig. 4):

- Building a conceptual ecosystem model describing stocks and flows of matter, by using biotic and abiotic functional entities and suitable properties for quantification.
- Collection of site-specific and generic data to use in a quantified mathematical representation of the conceptual model, describing stocks and flows of matter at suitable units of resolution.
- Describing and quantifying processes affecting flow and accumulation of matter within terrestrial, limnic and marine ecosystems and across their boundaries.
- Construction of a site-specific, linked ecosystem-landscape model, describing flow and accumulation of matter (carbon) among terrestrial, limnic and marine ecosystems.

1. Building the conceptual ecosystem model and categorization. As a starting point, a conceptual model was constructed to identify essential properties affecting the stocks and flows of matter in ecosystems (Fig. 3 in Box 1). This model was not primarily based on site-specific information, but rather built upon literature and expertise from different fields of science (34). The generic conceptual model was then adjusted to a site-specific conceptual model. One of the more difficult tasks when constructing the model was to find a suitable categorization and classification of the landscape into more easily handled units. The landscape was at this point divided into three ecosystems; terrestrial, limnic and marine. Each of these was then subdivided into site-specific ecosystems, e.g. forest, mire, lake and bay. Further classification was done using functional units

Box 1. A conceptual scenario for transport of radionuclides from the bedrock to the biosphere.

The transport of radionuclides from the geosphere to the biosphere may follow an array of different pathways leading to human exposure. Below, we present a possible scenario by describing the complex transport of a single radionuclide passing through the geosphere and biosphere ecosystems. The hypothetical pathway of a radionuclide is shown as a pink dotted line. The entry point to the hydrological model is scenario point **1**.

A radionuclide is released from its origin, a repository at 500 m depth. After being transported in the geosphere for some 100 to 1000 years it approaches the ground surface. When the radionuclide reaches a depth of 20 m below the surface, it strikes a horizontal fracture in the bedrock with a massive water flow (scenario point **2**). A sub-surface horizontal fracture leads to a larger zone of complex fractures, below a valley. The radionuclide leaves the geosphere and transport temporarily ceases in the matrix that constitutes the transition zone between the rock and the soil domains. During snow melt, the radionuclide moves upwards, together with the water table, and is incorporated into a sandy layer, derived from glaciofluvial deposition. Such matter is a highly suitable medium for radionuclide transportation, and over the next few years the radionuclide is transported along the valley by hydrological processes at a depth of 3 m. High precipitation helps transport the radionuclide through the soil stratigraphy to a till layer at the bottom of a creek, finally ending up in a mixed overland flow and a mire complex. The turnover time of mires is slow, hence the radionuclide accumulates in the sediment of the wetland for the next couple of hundred years. Due to changes in land use, e.g. draining the wetland for forestry purposes, the radionuclide is released again, and follows the water table at around 50 cm depth. The radionuclide enters the food web when a root from a tree transports it, together with water, up the xylem inside the stem. While inside the tree, the radionuclide is used as a building block in the biomass before it reaches a branch and falls to the ground as dead matter (scenario point **3**). Fungi living on dead wood accumulate the radionuclide, which is eaten by a roe deer. When the roe deer dies, the radionuclide is released and ends up by the shore of a lake. The radionuclide now moves towards the lake due to bioturbation and unsaturated water flow. While inside the lake water mass (scenario point **4**), it attaches to a humus particle and is transported within the lake ecosystem. Finally, the radionuclide flows through the outlet of the lake and flows towards the sea and into a fish gill (scenario point **5**). The fish is caught by a man and eaten. The radionuclide, now inside a human, becomes unstable and decays, creating an atom of a stable element, and a dose to the human.

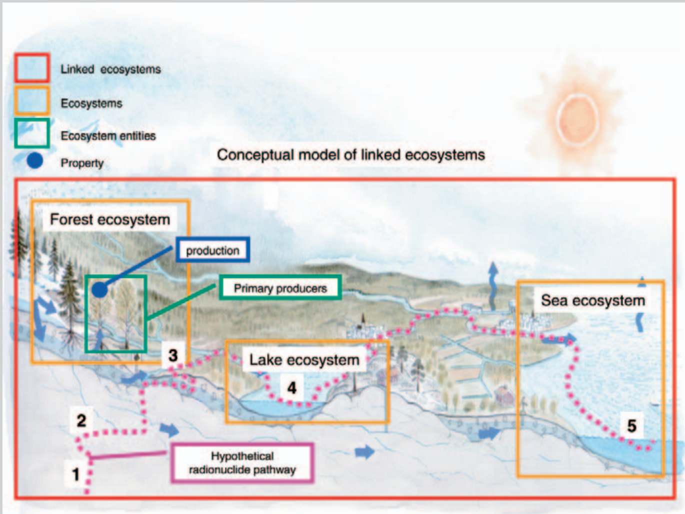

Figure 3. A conceptual model of a site, illustrating rock, regolith, soil, biota and hydrology. The hypothetical path of a radionuclide is shown as a pink dotted line. (1) The nuclide enters the hydrological flow model. (2) The fractured upper part of the rock and the mixed rock/soil domain and its water flow is modeled. (3) A hydrological model describes the surface flow path. (4 and 5) The discharge into ecosystems e.g. mires, running waters, lakes and agricultural land and eventual transport to the sea.

that potentially constituted a basis for budget calculations of stocks and flows of organic matter. The units were further divided on the basis of functional groups within the food web.

The watershed was used as a fundamental unit for the terrestrial system, in which both hydrology and transport of matter were modeled (27). Similarly, the use of lakes as fundamental units was determined by the possibility of monitoring each lake separately, and because the categorization of lake habitats could be undertaken using an existing classification system of habitats (35, 36), in which the whole lake drainage area type is used together with the lake parameters to classify the lake and the lake habitats.

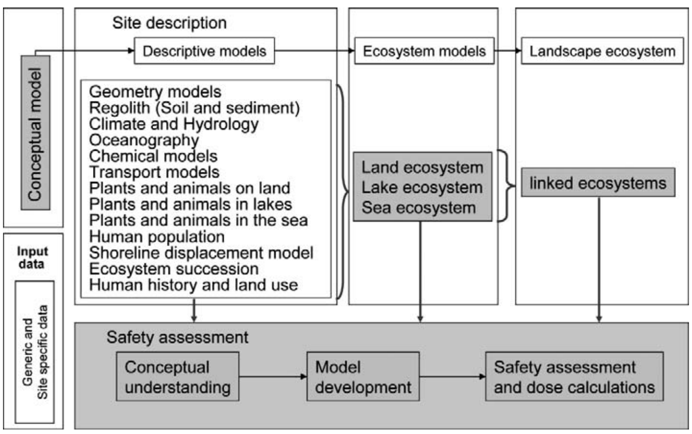

Figure 4. The process of building a site-descriptive ecosystem model. The site is defined and a conceptual model is constructed by describing functional units, and the fluxes between them. Data are collected at the site in order to describe the biotic and abiotic properties in the conceptual model. The landscape is divided into a number of spatially distributed models using site data and a GIS. Flows and accumulations of matter are described using hydrological tools, drainage areas and site data. All information is compiled into a site-specific ecosystem model.

2. Data collection. Field surveys and data collection were planned based on the properties defined in the conceptual model. Data were collected during site investigations at the two potential sites for a future repository (Fig. 2) (site-specific data), or were obtained from public databases and literature (generic data). The site investigation and its discipline-specific methodology are not described in this paper (but see 3). Data collected in the field were, e.g., vegetation cover, land use, species data, soil properties, hydrological properties. Based on these data, budgets of organic matter in terrestrial systems may be described in terms of biomass, primary production, secondary production, decomposition, mineralization, and soil organic matter content and composition (30), and in lake and sea ecosystems in terms of biomass, primary production, secondary production, decomposition and water chemistry (31, 33, 37). The conceptual model also includes abiotic factors of importance for vertical or horizontal transport of matter, such as precipitation, evapotranspiration, respiration and groundwater movement (27).

The conceptual model, and the methodology described at that stage, is the foundation for the site investigation program, including field sampling and a data collection program. The site-specific data are stored in a database and presented or modeled in a geographical information system (GIS) covering the specific area. The spatial resolution of the data is context dependent. The resolution of data from the terrestrial landscape is a function of the resolution of satellite classification techniques and the diversity of major vegetation types. Some of the models, e.g. the marine and lake models described in Wijnbladh et al. (33) or Sobek et al. (31), use site-specific data to a large extent, whereas other models, e.g. the forest model, discussed in Karlberg et al. (29), use site-specific data to a lesser extent. In order to assess doses to humans, given the calculated distribution of radionuclides in the landscape, a number of assumptions were made concerning human activities and land use, cf. Jansson et al. (12). Many of these assumptions are based on generic data, but the characteristics of the site and its potential future states provide a number of constraints on the assumptions made.

3. Describing and quantifying processes within ecosystems. At this stage, the data were evaluated and if necessary complementary data were collected in the field, or existing data were reorganized, e.g. due to reconsideration of the functional units. The two potential sites for a future repository for spent nuclear fuel are both situated on the coast of the Baltic Sea and include a large number of different ecosystem types, such as forests, agriculture land, wetlands, lakes and the sea. Based on the conceptual model, we used site-specific data to establish local budgets of standing stocks and flows of matter for the different units of resolution at an ecosystem level. By using overlayering techniques in a geographical information system (GIS), data were merged to make spatially distributed estimates of standing organic biomass for different functional units such as tree layer, shrub layer, field layer and ground layer. Carbon was used to describe stocks and flows of matter, as it is more or less interchangeable as currency with energy and biomass because of the relative constancy of carbon and energy contents in organic matter (e.g. 23). Carbon, nitrogen, and phosphorus are often found in relatively constant stoichiometric relationships within different functional groups and these relationships may differ between ecosystems, e.g. terrestrial and limnic systems (38). By also estimating stocks and flows of other elements, which have various stoichiometric relationships with carbon, errors in estimation of stocks and flows of energy, matter, nutrients and contaminants may be minimized. Although the behavior of radionuclides associated with organic matter is unique for each radionuclide, a major radionuclide pathway to humans in the safety assessment is via digestion and thus follows the organic matter in the ecosystem (see Avila et al. (14)).

The terrestrial model. In a terrestrial system, organic matter is recycled between organisms in the food web and the physical environment, and may also accumulate as peat. Accumulation often means that the organic matter is no longer involved in short-term recycling, and some kind of disturbance in the long-term cycle has to occur to release it into circulation again, e.g. people start to plough old lake beds or harvest peat. In long-term cycling, matter leaches from the terrestrial ecosystem into streams, follows watercourses into lakes, and finally discharges into the sea. By estimating inflows and outflows of organic matter in different ecosystems, it is possible to set limits on the potential variations by setting the physical and biological limits for estimations of, e.g., carbon accumulation in peat land.

The descriptive terrestrial ecosystem model, further presented in Löfgren et al (30), describes the pools and fluxes of carbon using GIS to distribute site-specific data in a landscape, delimited by water divides. The biomass pool and net primary production was estimated for the functional groups; tree, field and bottom layer both above and below ground. Above-ground litter flux was estimated using a quotient between the

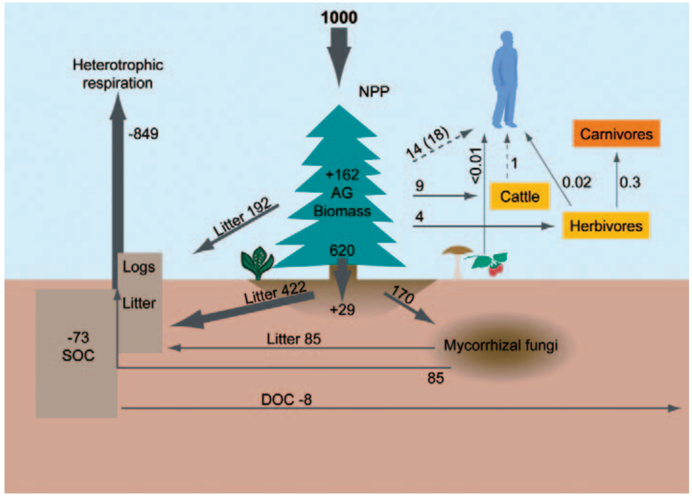

Figure 5. The fate of 1000 g of carbon assimilated by autotrophs (net primary production) during one year in the Simpevarp area. Figures within compartments denote a change in their carbon content while arrows are fluxes. The mismatch when summing figures describing the biomass is due to threshing and straw loss for the flux from crops to humans, and because cattle and herbivore consumption have not been excluded from the biomass. The two dashed arrows are fluxes expected under certain assumptions of human land use, divided between crops and fodder for cattle. The figure within brackets is the carbon flow to humans growing barley on all arable land in the area. (cf. Löfgren et al. (29)).

production of small branch and needle litter, and their standing biomass from a nearby locality. Yearly turnover of roots was assumed to equal the total biomass of the fine roots for all tree categories. Soil respiration, soil temperature and soil moisture was measured for five different vegetation types. Soil organic carbon was estimated down to approximately 1 m below ground surface, including litter and humus horizons and mineral soil among nine soil types. The biomass, consumption and production of herbivores and carnivores were estimated, based on densities in the area.

The carbon budgets presented in Löfgren et al. (30) for one of the potential repository sites (Simpevarp) showed that net primary production (NPP), including tree, field, ground layers and mycorrhizal fungi, ranged from 432 g C m^{-2} y^{-1} to 709 g C m^{-2} y^{-1} for 14 different catchments, with a mean value of 593 g C m^{-2} y^{-1} for the whole modeled area. The NPP can be used as an upper estimate of the potential incorporation of bioavailable radionuclides into biomass and, consequently, this potential accumulation varies by a factor 2 between catchments. The net ecosystem production for the whole area was positive suggesting that there is a net yearly accumulation of carbon. This accumulation was predominately found in biomass, whereas the soil organic carbon pool was a source for carbon emission, within the Simpevarp area (Fig. 5).

The aquatic models. In the marine model, presented by Wijnbladh et al. (33), the spatial domain consists of 600 × 700 cells with a size of 20x20 m, using GIS. This grid is used to model the fluxes of carbon between functional groups and the surrounding environment. Averages of the modelling calculations are made for hydrographically distinct areas (inner- or outer basins). The distribution and flux of carbon within each grid cell is described by a food-web model and the abiotic component by dissolved inorganic carbon and particulate organic carbon. The primary producers included in the model are benthic micro- and macrophytes and phytoplankton, and the consumers are bacterioplankton, zooplankton, fish, benthic herbivores, filter feeders, carnivores and detritivores, benthic bacteria, birds, and humans. All compartments were connected by the processes net primary production, respiration, consumption, feces production and excess excretion. The processes are constrained by temperature, light intensity and inorganic carbon available for primary production. The biomasses and biotic process values are considered to be fixed and independent of each other and no fluxes between the grid-cells were included. Advective transport of carbon between the basins is calculated from differences in carbon concentration and average annual flux of water between basins. These annual averages were obtained from 3D-circulation models in the same fashion as presented in Engqvist et al. (28). The results from each grid cell in the model calculation were then integrated for each basin, thus creating data usable in a linked landscape model (15). In that model, estimations of advective water fluxes between the basins are included as well as fluxes between limnic and terrestrial ecosystems.

In contrast to terrestrial and marine models, the limnic model (31) uses a mass balance approach, where pools of dissolved organic carbon, particulate organic carbon and dissolved inorganic carbon are calculated by multiplying the average concentration in surface and bottom waters with the total volume of the lake. For the calculation of the pool size and accumulation rate of carbon in sediments, it is assumed that profundal sediments correspond to areas with accumulation bottoms, see Sobek et al. (31) and Andersson and Sobek (32).

4. Linking ecosystem models. Individual ecosystem models are transformed into a linked ecosystem model to predict how and where matter is accumulated. During such integration, a number of simplifying assumptions have to be made. However, it is always possible to back-track information in more detail, if necessary, by using the extensive site-specific database. This approach ensures that many of the simplifying assumptions made when going from one step to another (Fig. 4), may be modeled and tested. If standing stocks and flows of matter are described accurately, we will have a baseline for making predictions of transport and accumulation of chemical elements or substances, such as radionuclides, released in the area, assuming that the transport of these substances follows that of carbon, though with some degree of discrimination in the various steps involved. Thus, the safety assessment is provided with a tool to predict how and where radionuclides are transported and accumulated in the landscape, making it possible to calculate potential dose to humans at the specific site (14, 37).

The ecosystems were connected by quantifying the input and output to/from each system. As the flow of surface water is the most important vector for transporting matter within and between systems (e.g. 35), it was subjected to quantitative modeling and simulation using site-specific data in order to understand the vertical and horizontal movement of surface water, on a catchment area basis, using topographically driven flow models like GIS and the MIKE SHE software (see Werner et al. (28) for a description of the hydrological modeling). The hydrological models were necessary to link different sub-areas and ecosystems within the landscape. Moreover, these models made it possible to calculate water turnover time for any chosen part of the site. The aquatic systems, as a part of the surface hydrology, are important for the transport of organic matter, but also for its accumulation in lake or seabed. Flows of matter in and between catchment areas are estimated from modeled hydrology and site data on water chemistry, thereby providing information on the transport of matter into running water, lakes and finally into the sea. By quantifying recharge and discharge it is possible to calculate input and loss of matter in a lake. The transport of matter in streams gives rise to the overall loss from the terrestrial systems, making it possible to compare modeled and observed losses from terrestrial systems.

The final recipient of the transported water and organic matter is the sea, where the water discharges. Transported solid matter is often accumulated in shallow bays, which consequently show large primary production due to high nutrient availability (39). Such bays also serve as the interface to the open sea, through which important exchange of matter may occur depending on water currents and bathymetry (28). For example, Kumblad et al. (13) show that there are small differences in the total carbon pool per unit area between the different ecosystems, although there is an obvious difference between the terrestrial and the aquatic ecosystems in the distribution of carbon between the biomass pool and the organic carbon in soil or sediment (SOC) pool. The median ratio between SOC and carbon biomass in the terrestrial ecosystem is 4 (range 2.3–5.0), whereas it is considerably larger (median 325) and highly variable (range 67–1075) in the limnic and marine ecosystems. This difference is mainly caused by the accumulation of carbon in terrestrial vegetation, in contrast to aquatic systems where accumulation of carbon over successive years in vegetation (including algae) is insignificant.

DISCUSSION AND APPLICATIONS FOR A SAFETY ASSESSMENT

One way to provide safety assessments of potential future radionuclide releases from a deep repository with a sound basis for radiological impact calculations is to use robust ecosystem models based on site-specific data. Our attempt to build such a spatial ecosystem model has proved that it is both feasible and useful for assessment purposes. The first methodological step, building a conceptual model, helped to define the properties needed to quantify processes important in the surface systems. It also provided early indications of what needed to be measured in the field and what type of methodology was needed during site investigations. However, the differences in sampling methodology between scientific disciplines, e.g. sampling frequency and type of variables or quantities, made it initially difficult to integrate the primary data into the models. Since one major challenge in this project is to integrate modeling of different ecosystems, built on different kinds of data and measures, future planning of site characterization (the forthcoming concluding investigation phase) will put more effort into using comparable sampling methods. The site investigations have shown that our initial conceptual model was generally appropriate, and only small changes were made (e.g. 5). Based on the functional entities described in the conceptual model, each discipline developed independent site-specific descriptions and models. Simultaneously, data were exchanged between disciplines, providing additional data for discipline-specific characterization, and a variety of opportunities to enhance the characterization of linkages between ecosystems and the functional understanding of landscapes. One example of integration and transdisciplinary collaboration is demonstrated by the digital elevation model (DEM) (e.g. 5, 27), used by all scientific disciplines during the modeling, leading to the use of the same grid size and the same hydrological forcing parameters, e.g. topography (4).

Temporal aspects of landscape development. The site descriptive model of the present-day biosphere also makes it possible to predict future processes that are essential for the safety assessment. This is important as several uncertainties affecting the model involve ecosystem variability over time. Climate change or variability due to the greenhouse effect is expected to influence important parameters in the biosphere such as the hydrological cycle, sea level, and the salinity of the Baltic Sea (e.g. 40). However, climatic alterations are often difficult to relate to a continuously changing environment, because the rate of change and variability of climate cannot easily be predicted. The expected magnitude and trends are mainly based on large-scale simulations, and site data have little to contribute to such studies. The variability in site data can, on the other hand, be used to study extreme situations under current climatic conditions. The biosphere changes at the potential sites during the next 1000 years are difficult to predict, but one of the most important changes is the natural infilling of lakes and slight withdrawal of the sea with consequent effects on the coastal basins (41, 42, 43).

The most important long-term external factors are shore-line displacement during glacial-interglacial cycles. For the marine ecosystem, which persists throughout the major part of the interglacial period, shore-line displacement has a significant effect on several model parameters affecting calculated radionuclide concentrations (44). Shore-line displacement also affects the persistence of lakes, transforming them into mires due to sedimentation and vegetation growth, and it may also constrain the life time of wells, agricultural land and mires, and thus the maximum time for radionuclide accumulation (44). These factors do not affect the surface system description presented in this paper directly, but do influence the selection of models in the safety assessment, e.g. the future local and regional development. In most cases, this is handled by selecting an appropriate configuration of ecosystems to provide a snapshot representation of the overall environment for each time period. A critical factor is how long an ecosystem exists before it changes into a new type of ecosystem, affecting the total amount of radionuclides accumulated in the system. The spatio-temporal aspects of ecosystem persistence and resilience are today frequently discussed in terms of different disturbance regimes, such as land use change (45, 46). It has been suggested that the likelihood of ecosystem shifts may increase with climate change, especially when humans reduce resilience by removing response diversity or functional groups of species, or removing whole trophic levels or impacting on ecosystems via emissions of waste and pollutants.

Spatio-temporal effects of land use. By including studies of current and historical human land use at the site, the multifunctionality of landscapes (47), often crucial for predicting landscape changes, is recognized. Knowledge of land use is crucial to calculating potential fluxes of carbon and hence radionuclides to humans. At present, this carbon flux is dominated by the contribution from the vegetation (30). Fluxes of carbon to humans from products derived from the local vegetation are often of the same magnitude as the herbivore consumption within a catchment area. However, if the land was used to produce maximum yield, i.e. by growing barley on all arable land, the flux of carbon from the vegetation to humans would increase by 30%, but would eliminate the lower carbon flux from cattle to humans (30). On the other hand, the flux of carbon to humans from hunting in such an area is low, suggesting that the largest potential fluxes to humans will occur within catchments having agricultural activities. These considerations will be taken into account in safety assessments to calculate the potential exposure of humans, depending on the population size and activities with regard to the use of locally produced food, and import and export of food.

One of the most important changes expected during the next 1000 years, besides climate change, relates to human exploitation of the sites. Human behavior is somewhat unpredictable, but a detailed description of historic land use in combination with information on the current conditions of the biosphere at the site, and projections of the development of local catchments during the next 1000 years, indicates constraints for human settlement, food and water supply. Future human exploitation of the environment at the sites in terms of farming, fishing, and hunting is estimated by predicting the availability of suitable soils, their productivity and water content, which in turn is based on the DEM and the marine geological maps (5, 42). In addition, old cadastral maps provide information on previous land use at the site, which can be used as a basis for estimating and validating land use in future scenarios (12). Landscape and ecosystem development in the coming 1000 years, and beyond, will contribute to estimating land use constraints, e.g. food production. For example, further analysis of the Quaternary deposits at the sites show that many current wetlands will be unsuitable for farming in the future, due to the presence of many large boulders in the soil. In the safety assessment dose modeling, efforts are made to model plausible future scenarios, and studies show that it is crucial to combine natural and social science, as these complex systems often, if not always, are associated with human-induced changes (48). Processes in ecosystem dynamics are also highly linked to how the social capacity responds to environmental feedback and change (46, 49)

CONCLUSIONS

This modeling approach, including the whole biosphere and its interconnected ecosystems, is a unique attempt to link ecosystem and landscape modeling. Few other studies have been made with the same aim, but see also Håkansson (50). In this study, we show that it is possible to construct a site-specific description of surface ecosystems, useful for a safety assessment for a deep repository for nuclear fuel. By using an integrated approach we can identify and quantify the processes affecting the transport and accumulation of matter within and among ecosystems at the potential sites. Although the overall aim is primarily to describe transport of radionuclides in the landscape, this approach to modeling, i.e. going from conceptual modeling and data collection to ecosystem modeling using *real* site data for validation, is also applicable when analyzing transport of other types of material, e.g. nutrients, at other sites, and for analyzing environmental effects of polluting industries, i.e. in Environmental Impact Assessments (EIA). In addition, analyses of current and historical land use can help to construct realistic models for future development at the sites. The safety assessment for a deep repository for spent nuclear fuel can use the surface-system descriptions as a tool to define and delimit the parameters used in dose models, and the environmental impact assessment for such a deep repository is provided with a detailed description to use in its analysis of consequences of developing and operating such a facility.

References and Notes

1. SKI. 2004. *Perspectives on Nuclear Waste*. Statens Kärnkraftsinspektion, Stockholm. (in Swedish).
2. SKB. 2004. *Programme for Research, Development and Demonstration of Methods for the Management and Disposal of Nuclear Waste, including Social Science Research*, SKB Report TR-04-21. Svensk Kärnbränslehantering AB. Stockholm, Sweden.
3. SKB. 2001. *Site Investigations. Investigation Methods and General Execution Programme*. SKB Report TR-01-29. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
4. Werner, K., Bosson, E. and Berglund, S. 2005. *Description of Climate, Surface Hydrology, and Near-surface Hydrogeology. Preliminary Site Description. Laxemar Ssubarea - Version 1.2.* SKB Report R-06-11. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
5. Lindborg, T. (editor). 2006. *Description of Surface Systems. Preliminary Site Description, Laxemar Subarea - Version 1.2.* SKB Report R-06-11. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
6. Lundin, L., Lode, E., Stendahl, J., Björkvald, L. and Hansson, J. 2005. *Soils and Site Types in the Oskarshamn Area. Oskarshamn SiteIinvestigation.* SKB Report R-05-15, Svensk Kärnbränslehantering AB, Stockholm, Sweden.
7. Tröjbom, M. and Söderbäck, B. 2006. *Chemical Characteristics of Surface Systems in the Simpevarp Area. Visualisation and Statistical Evaluation of Data from Surface Water, Precipitation, Shallow Groundwater, and Regolith.* SKB Report R-06-18, Svensk Kärnbränslehantering AB, Stockholm, Sweden.
8. Berg, J., Jansson, U. and Wästfelt, A. 2006. *Landscape, History and People in a Geographical Perspective–Studies of Land-use, Settlement and Livelihood in Oskarshamn and Forsmark.* SKB Report R-06-37, Svensk Kärnbränslehantering AB, Stockholm, Sweden.
9. Naveh, Z. 2001. What is holistic landscape ecology? A conceptual introduction. *Landscape Urban Plan. 50*, 7–21.
10. Tress, B., Tress, G., Décamps, H. and d'Hauteserre, A.M. 2001. Bridging human and . natural science in landscape research. *Landscape Urban Plan. 57*, 137–141.
11. Antrop, M. 2001. Landscape change and the urbanization process in Europe. *Landscape Urban Plan. 67*, 9–24.

12. Jansson, U., Kautsky, U. and Miliander, S. 2006. Rural landscape, production and human consumption: Past, present and future. *Ambio 35*, 505–512.
13. Kumblad, L., Söderbäck, B., Löfgren, A., Lindborg, T., Wijnbladh, E. and Kautsky, U. 2006. Pools and fluxes of organic matter in a boreal landscape: Implications for a safety assessment of a repository for nuclear waste. *Ambio 35*, 496–504.
14. Avila, R., Kautsky, U. and Ekström, P.-A. 2006. Modeling the long-term transport and accumulation of radionuclides in the landscape for derivation of dose conversion factors. *Ambio 35*, 513–523.
15. Kumblad, L., Kautsky, U. and Naeslund, B. 2006. Transport and fate of radionuclides in aquatic environments–The use of ecosystem modeling for exposure assessments of nuclear facilities, *J. Environ. Radioactiv. 87*, 107–129.
16. Turner, M.G. 2005. Landscape ecology: What is the state of the science? *Annu. Rev. Ecol. Evol. Syst. 3*, 319–44.
17. Bell, S.S., Robbins, B.D. and Jensen, S.L. 1999. Gap dynamics in a seagrass landscape. *Ecosystems 2*, 493–504.
18. Ward, J.V., Malard, F. and Tockner, K. 2002. Landscape ecology: a framework for integrating pattern and process in river corridors. *Landsc. Ecol. 17*, (Suppl.), 35–45.
19. Soranno, P.A., Webster, K.E., Riera, J.L., Kratz, T.K., Baron, J.S., Bukaveckas, P.A., Kling, G.W., White, D.S., et al. 1999. Spatial variation among lakes within landscapes: ecological organization along lake chains. *Ecosystems 2*, 395–410.
20. Loreau, M., Mouquet, N. and Holt, R.D. 2003. Metaecosystems: a theoretical framework for a spatial ecosystem ecology. *Ecol. Lett.* 6, 673– 79.
21. Burke, I.C., Lauenroth, W.K., Cunfer, G., Barrett, J.E., Mosier, A. and Lowe, P. 2002. Nitrogen in the central grasslands region of the United States. *BioScience 52*, 813–23.
22. Groffman, P.M., Tiedje, T.M., Mokma, D.L. and Simkins, S. 1992. Regional-scale analysis of denitrification in north temperate forest soils. *Landsc. Ecol. 7*, 45–54.
23. Chapin, F.S. III, Matson, P.A. and Mooney, H.A. 2002. *Principles of Terrestrial Ecosystem Ecology*. Springer-Verlag, New York, 436 pp.
24. Reiners, W.A. and Driese, K.L. 2004. *Transport Processes in Nature*. Cambridge Univ. Press, Cambridge, UK, 302 pp.
25. Gardner, R.H., Dale, V.H., O'Neill, R.V. and Turner, M.G. 1992. A percolation model of ecological flows. In: *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flow*. Hansen, A.J. and Castri, F.D. (eds.). Springer-Verlag, New York, NY, pp. 259–269.
26. Costanza, R., Voinov, A., Boumans, R., Maxwell, T., Villa, F., Wainger, L. and Voinov, H. 2002. Integrated ecological economic modeling of the Patuxent River watershed, Maryland. *Ecol. Monogr. 72*, 203–32.
27. Werner, K., Bosson, E. and Berglund, S. 2006. Analysis of water flow paths: Methodology and example calculations for a potential geological repository in Sweden. *Ambio 35*, 425–434.
28. Engqvist, A., Döös, K. and Andrejev, O. 2006. Modeling water exchange and contaminant transport through a Baltic coastal region. *Ambio 35*, 435–447.
29. Karlberg, L., Gustafsson, D. and Jansson, P.-E. 2006. Modeling carbon turnover in five terrestrial ecosystems in the boreal zone using multiple criteria of acceptance. *Ambio 35*, 448–458.
30. Löfgren, A., Miliander, S., Truvé, J. and Lindborg, T. 2006. Carbon budgets for catchments across a managed landscape mosaic in southeast Sweden: Contributing to the safety assessment of a nuclear waste repository. *Ambio 35*, 459–468.
31. Sobek, S., Söderbäck, B., Karlsson, S., Andersson, E. and Brunberg, A.-K. 2006. A carbon budget of a small humic lake: An example of the importance of lakes for organic matter cycling in boreal catchments. *Ambio 35*, 469–475.
32. Andersson, E. and Sobek, S. 2006. Comparison of a mass balance and an ecosystem model approach when evaluating the carbon cycling in a lake ecosystem. *Ambio 35*, 476–483.
33. Wijnbladh, E., Jönsson, B.F. and Kumblad, L. 2006. Marine ecosystem modeling beyond the box: Using GIS to study carbon fluxes in a coastal ecosystem. *Ambio 35*, 484–495.
34. Löfgren, A. and Lindborg, T. 2003. *A Descriptive Ecosystem Model–A Strategy for Model Development During Site Investigations*. SKB Report R-03-06. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
35. Blomqvist, P., Brunberg, A.-K. and Brydsten, L. 2000. *Lake and Lake Related Drainage Area Parameters for Site Investigation Program*. SKB Report R-00-38, Svensk Kärnbränslehantering AB, Stockholm, Sweden.
36. Brunberg, A.-K., Carlsson, T., Brydsten, L. and Strömgren, M. 2004. *Identification of Catchments, Lake-related Drainage Parameters and Lake Habitats*. Oskarshamn Site Investigation SKB Report P-04-242, Svensk Kärnbränslehantering AB, Stockholm, Sweden.
37. Kumblad, L., Gilek, M., Næslund, B. and Kautsky, U. 2003. An ecosystem model of the environmental transport and fate of carbon-14 in a bay of the Baltic Sea, Sweden. *Ecol. Model. 166*, 193–210.
38. Sterner, R.W. and Elser, J.J. 2002. *Ecological Stoichiometry*. Princeton University Press, Princeton, USA, 439 pp.
39. Kautsky, U. 1995. *Ecosystem Processes in coastal areas of the Baltic Sea*. Ph.D. thesis, Department of Zoology, Stockholm University, Stockholm, Sweden.
40. Gustafsson, B. 2004. Sensitivity of the Baltic Sea salinity to large perturbations in climate. *Clim. Res. 27*, 237–251.
41. Brydsten, L. 2004. *A Mathematical Model for Lake Ontogeny in Terms of Filling with Sediments and Macrophyte Vegetation*. SKB Report TR-04-09. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
42. Brydsten, L and Strömgren, M. 2005. *Digital Elevation Models for Site Investigation Programme in Oskarshamn*. Site description Version 1.2. SKB Report R-05-38. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
43. Brydsten, L., Carlsson, T., Brunberg, A. and Blomqvist, P. 2004. *A Method for Determination of Morphometry, Sediment Distribution, and Habitat Diversity of Lake Basins and Its Application to Three Lakes in Uppland*. SKB Report R-04-40. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
44. SKB. 2004. *Interim Main Report of the Safety Assessment SR-Can*. SKB Report TR-04-11. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
45. Bengtsson, J., Angelstam, P., Elmqvist, T., Emanuelsson, U., Folke, C., Ihse, M., Moberg, F. and Nystrom, M. 2003. Reserves, resilience and dynamic landscapes. *Ambio 32*, 389–396.
46. Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. and Holling, C.S. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev. of Ecol. Syst. 35*, 557–581.
47. Fry, G.L.A. 2001. Multifunctional landscapes – towards trandisciplinary research. *Landscape Urban Plan. 57*, 159–168.
48. Bürgi, M., Hersperger, A.M. and Schneeberger, N. 2004. Driving forces of landscape change – current and new directions. *Landscape Ecol. 19*, 857–868.
49. Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S. and Walker, B. 2002. Resilience and sustainable development: Building adaptive capacity in a world of transformations. *Ambio 31*, 437–440.
50. Håkansson, L. 2004. Modelling the transport of radionuclides from land to water. *J Environ. Radioactiv. 73*, 267–287.
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