International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Quantitative Assessment of Natural and Anthropogenic Factors in Forest Carbon Sequestration

Peter A. Khaiter[a], Marina G. Erechtchoukova[a]
[a]*School of Information Technology, Faculty of Liberal Arts and Professional Studies, York University*
4700 Keele Street, Toronto, Ontario, M3J 1P3 Canada
pkhaiter@yorku.ca

Abstract: The ability of the ecosystems to generate services is vital for human well-being, economic development and even survival. The production of ecosystem services is influenced by a complex interplay of natural and anthropogenic factors. Quantitative assessment of the ecosystem services as well as natural and anthropogenic factors affecting them is a crucial aspect of sustainable environmental development and management. The paper discusses a theoretical framework for quantifying ecosystem services and their changes in response to natural and anthropogenic factors on the basis of a meta-modelling approach. The effect of anthropogenic factors on the ecosystem components and services is modelled using corresponding transformation functions. Forest ecosystems and their services, with a special emphasis on the role of forests in carbon cycling and sequestration, are considered.

***Keywords**:* Ecosystem services; sustainable environmental management; natural and anthropogenic factors; forest ecosystem; carbon sequestration.

1 INTRODUCTION

It is widely recognized that ecological systems provide a diverse spectrum of services that, directly or indirectly, support life on the planet and are thus vital for human well-being, economic development and even survival. Ecosystem services can be interpreted as the benefits obtained by people from ecosystem functioning or existence. In a state-of-the-art study of the Earth’s ecosystems carried out under the UN-led Millennium Ecosystem Assessment initiative [MA 2005], ecosystem services have been classified in four broad groups: *provisioning*, such as the production of food and water; *regulating*, such as the control of climate and disease; *supporting*, such as nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefits. An appraisal of the current state and trends in the world’s ecosystems and their services was focused on 24 services related to 10 ecosystem types (marine fisheries, coastal, inland waters, forest and woodland, dryland, island, mountain, polar, cultivated, and urban) and it revealed alarming signs of the ongoing degradation in at least 15 of 24 services assessed due to the harmful anthropogenic impacts being caused by the humankind, especially in the last 50 years.

For the practices of sustainable environmental management, the policy- and decision-makers need to clearly understand any possible impact on the ecosystems’ ability to deliver the services under different scenarios of societal development. Given an open nature of ecological systems [von Bertalanffy 1969], their dynamics, including the production of services, is formed by an interplay of natural and anthropogenic factors. Quantitative assessment of the ecosystem services as well as natural and anthropogenic factors affecting ecosystems functioning and the ability to generate the services becomes a crucial aspect of sustainable environmental development and management [Khaiter 2005a, 2005b, Khaiter and Erechtchoukova 2007]. A theoretical framework for quantifying ecosystem services and their changes in response to natural and anthropogenic factors on the basis of a meta-modelling approach is discussed in the subsequent sections. The paper considers the forest ecosystems and their services making a special emphasis on the role of forests in carbon cycling and sequestration.

2 METHODOLOGY

In application to environmental issues, sustainability is understood as maintaining natural capital and resources [Goodland 1995]. Barett and Odum [2000] suggested that sustainable development may be viewed in terms of the concept of the optimum carrying capacity in the same way as it is used in ecology to determine the upper limits for basic structures and functions of a given ecosystem that can be sustained by the available incoming energy over long periods in the face of environmental uncertainties.

It is obvious that sustainable management of natural resources and environmental systems requires an adequate consideration of various ecological and socio-economic services provided by ecosystems. An idea of sustainable environmental management is only possible if multiple goods and services generated by an ecosystem are properly identified, quantified, valuated and incorporated into the decision-making process [Khaiter 2005b]. The most favourable strategy of development can be chosen from the criterion of maximum net environmental value (MNEV) of the set of complementary ecosystem goods and services. A practical implementation of this interpretation of environmental sustainability requires a framework incorporating at the very minimum the following elements: (1) an adequate theoretical understanding of an ecosystem and its multiple services; (2) an adequate model of an ecosystem describing internal physical, chemical, and biological processes and their interrelationships, structure and components of the ecosystem, laws of its functioning and generation of the services under natural conditions; (3) understanding of the principles governing responses/reactions of the ecosystems to exogenously caused stresses including the ability to produce services; and (4) a model predicting the ecosystem behaviour under the anthropogenic impacts and the quantities of the services which incorporates simulation modelling, economic valuation and methods of optimization within a single theoretical approach [Khaiter and Erechtchoukova 2010].

3 METHODS

In general systems theory [von Bertalanffy 1969], any system is characterized by: (1) the structure (i.e., parts and their composition); (2) behaviour (i.e., inputs, internal processing and outputs of material, energy or information); (3) interconnectivity (i.e., functional as well as structural relationships between the various parts of a system); and (4) emergentness (i.e., properties and functions arising out of combining the ecosystem components within a single whole structure).

In accordance with the general systemology, a natural ecosystem can be defined as an independent spatiotemporal unit of interrelated living (biotic) components interacting with non-living (abiotic) factors and the processes governing functioning and structure of the ecosystem components [e.g. Mueller 1997, Odum 1983]. A model for the evolution of an ecosystem can be expressed as follows:

$$M[t,\ \mathbf{in}(t), \mathbf{x}(t), \mathbf{p}(t),\ \mathbf{F}(t)] \ = \ 0, \qquad (1)$$

where M is the model dynamics operator; t is the time variable; $\mathbf{x}(t)$ is a non-negative state vector, coordinates of which quantitatively designate biotic and abiotic constituencies of the ecosystem and their properties, such as richness and density of species or their assemblages, concentrations of organic and inorganic matters and polluting substances, etc.; $\mathbf{p}(t)$ is a vector of ecosystem parameters; $\mathbf{in}(t)$ is a vector of incoming inputs of environmental factors; $\mathbf{F}(t)$ is a vector-function of ecosystem processes which represent an interplay of environmental inputs, state variables and parameters.

When analyzing ecosystem dynamic behaviour, it is important to differentiate between the contribution of natural factors and the impact caused by anthropogenic factors making a particular emphasis on anthropogenic stress for the following reasons [Khaiter and Erechtchoukova 2007]: (1) anthropogenic stress alters the rate of the ecosystem development, dramatically speeding it up in the most of the cases; (2) human-caused disturbances are novel and, hence, "unfamiliar" to the ecosystem, which means that there are no evolutionary developed compensatory reactions or adaptive mechanisms within the ecosystem to cope with and sustain the stress. Evolution model (1) describes ecosystem behaviour under the natural factors and can serve as a base-model level 0, *BaseModel0*. If $\mathbf{u}(t)$ represents management strategies, ecosystem anthropogenic dynamics can be interpreted as a meta-model of the base-model:

$$MetaModel1 = BaseModel0(\mathbf{u}). \quad (2)$$

Building the transformations *BaseModel0* → *MetaModel1* is a substantially non-trivial task which requires extensive observation data on the behaviour of the ecosystem components as they respond to each kind of anthropogenic stress and combinations thereof.

4 FOREST ECOSYSTEMS AND CARBON SEQUESTRATION

4.1 Forests as multiple service providers

A unique role of forests among other ecosystems is determined by the fact that few ecosystems can generate as many services as forests. They provide overall ecosystem health and sustainability, protect water and air quality, support biodiversity and wildlife habitats, supply recreation and aesthetic enjoyment, etc. An overview on this issue can be found, e.g., in [Dale 1998].

In order to accommodate the multifunctional role of forests within a single theoretical approach, the concept of a *forest ecological-economic-social* (FEES) system has been proposed [Khaiter 1991, 1996, 2005b, Gorstko and Khaiter, 1991]. According to this concept, the set of possible forest-related services can be classified into three main categories: (1) *ecological* amenities that combine protective and conservational influences on the environment; (2) *economic* amenities related to the generation of food, fodder, and industrial raw materials that are used or that can be potentially used by an economy; and (3) *social* amenities that include the creation of comfortable conditions for humans from sanitary, cultural, aesthetical, recreational, and environmental points-of-view. A sample list of forest benefits in each of these three categories is shown in Table 1.

Contemporary global climate change [e.g. Houghton et al. 1995] stimulated a better understanding of an increasing role of forests in greenhouse gases reduction [e.g., Potter et al. 2001] and nutrient cycling [e.g. Blanco et al. 2005]. At the same time, recent studies [e.g. Aber et al. 2001] suggested that climate change, in its turn, affects forest ecosystems and revealed a sophisticated interplay between natural dynamics, human-induced influence, forest disturbances and climate change. These mechanisms should be accounted for in quantifying the forest ecosystem services.

Table 1 Three categories of forest benefits.

Economic amenities	Ecological amenities	Social amenities
Wood products (timber and fuel wood) Non-timber products: • wild food (honey, mushrooms, wild fruits and latex, berries, fibers, nuts, hunting meat from wild animals, birds, and fish) • raw material (cork, resin, mastic gum) • medicinal plants • plant genetic resources	Landscape stabilization Soil protection from erosion Soil moisturizing Soil enrichment by nutrients (fertilization) Pest control Water quantity regulation (hydrological function) Water purification (hydrochemical function) Flood control Climate regulation Carbon sequestration Oxygen generation Global warming mitigation Fisheries protection Wildlife habitat	Human habitat function Recreation opportunities Tourist opportunities Aesthetic function Sanitary functions: • Disease buffering • Therapeutic • Dust sequestration • Noise reduction Educational function

4.2 Quantifying forest services

Quantitative values of ecosystem services can be considered as the outputs of the forest ecosystem model, like *BaseModel0*, in a case of natural dynamics or *MetaModel1* in a case of anthropogenic dynamics and appears as *MetaModel2*. It should be noted that there is no analytic expression for *BaseModel0*, *MetaModel1* or *MetaModel2*. In most cases, they can only be formalized by building complex process-based simulation models. As Costanza and Folke [1997] put it, “one way to get at these values would be to employ systems-simulation models that incorporate the major linkages in the system at the appropriate time and space scales.”

For example, to quantify the hydrological service of a forest, an approach has been suggested [Khaiter 1993] that is based on a simulation modelling “Forest hydrology” (SMFH) of the processes of moisture transformation in a forested watershed. The SMFH simulates the processes of forest hydrology, and produces as outputs the values of the water balance components, and provides a quantitative assessment of the hydrological service of the forest under different management scenarios.

4.3 Forest and carbon cycles

Along with other terrestrial and marine ecosystems, forests are an important carbon sink. For example, Canadian forests cover an estimate area of 303 million hectares and store an estimate of 95 Gt of carbon [Henschel and Gray 2007, Roulet 2000]. A comparison of different Canadian forest regions revealed that boreal forests store more carbon than any other forest types [Henschel and Gray 2007, Kurz 1999]. The ability to sequester atmospheric carbon dioxide and accumulate carbon in biomass (trunks, branches, foliage, and roots) and soils makes forest ecosystems an important component of climate change mitigation and, broadly, global environmental sustainability.

Carbon accumulation in forests is the balance of gross primary production (photosynthesis) and ecosystem respiration. There is a wide range of processes and factors that influence and control carbon dynamics in forest ecosystems and may cause substantially multiplicative effects. As noted by Pregitzer and Euskirchen [2004], even small shifts in the [carbon] balance can result in a large change in the uptake or emission of CO_2. These effects should be quantified and incorporated in the models.

4.4 Forest carbon pools

Physical, chemical and biological processes controlling carbon fluxes in a forest ecosystem take place in its different components, called carbon pools. In quantifying carbon budget, the following pools can be distinguished: foliage, fine branch, large wood, fine root, and coarse root, non-tree vegetation, litter, organic soil to a depth of 1 m (including peat) and mineral soil (Fig. 1).

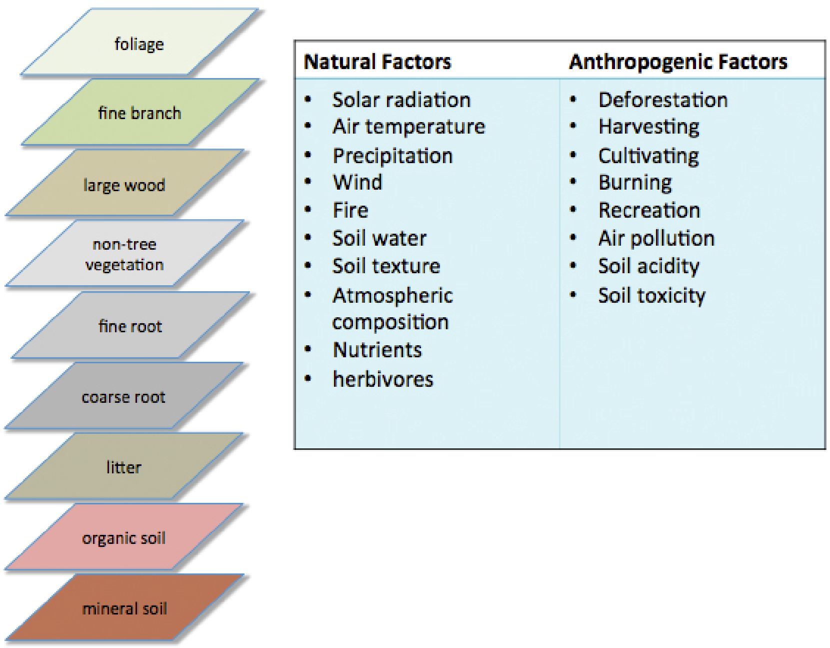

Figure 1 Forest carbon pools, natural and anthropogenic factors.

In each pool, carbon may appear in different forms. For example, soil carbon can be present as soil organic carbon (SOC) and soil inorganic carbon (SIC) while in-water carbon can be considered as dissolved organic carbon (DIC), dissolved carbon dioxide (DCO2), dissolved bicarbonate (DBC), dissolved organic carbon (DOC) and particulate organic carbon (POC). The balance condition should obviously be satisfied for each carbon pool:

$$\frac{dC^j}{dt} = \sum_i INC_i^j - \sum_k OUT_k^j \,, \qquad (3)$$

where j denotes a carbon pool; C^j is the carbon contents in the jth carbon pool; t is the time variable; INC_i^j, OUT_k^j are the ith incoming flux and kth outcoming flux, respectively, for the jth carbon pool. Soil is the main carbon sink in forest. As estimated [Dixon 1994], over two-thirds of the carbon in the global forest ecosystems is contained in soils and associated peat depositions. Recent publications argue for a more detailed soil module in the carbon-inventory models including different groups of micro-organisms. For example, a soil module developed for the ANAFORE forest model includes three functional groups of micro-organisms (bacteria, mycorrhizal fungi and non-mycorrhizal fungi) that degrade and translocate organic compounds in nine mineral layers [Deckmyn et al. 2011].

4.5 Natural and anthropogenic factors

Carbon cycles in each pool are affected by natural factors. In quantifying the dynamics of forest carbon recycling and sequestration, the most important natural factors are: air temperature, solar radiation, precipitation, wind, fire, soil water content, soil texture, atmospheric composition, nutrients, and herbivore [Koo et al. 2011, Scheller et al. 2011] (Fig. 1). In quantitative assessment of the anthropogenic factors in the ecosystem dynamics, it is important to distinguish between two kinds of stress: (1) a direct impact on abiotic part of the ecosystem (A-stress); and (2) a direct impact on ecosystem biotic assemblages (B-stress) as well as understand the patterns in ecosystem stress dynamics [Khaiter and Erechtchoukova 2007].

Human-induced impact onto forest ecosystems can be caused, e.g. by deforestation, harvesting, cultivation, burning, recreation, air pollution, soil acidity and toxicity (Fig. 1). Important that large quantities of carbon accumulated in forest ecosystems for decades to centuries can be released to the atmosphere over short periods of time following disturbance [Pregitzer and Euskirchen 2004, Koerner 2003]. To formalize the anthropogenic dynamics of the FEES, that is, the transformations from naturally controlled conditions to the anthropogenically impacted states as specified by the Eq. 2, it is suggested to use functions of anthropogenic impact (FAI) for the corresponding management activity u_k. A sample study on building the transformation functions for forest ecosystems can be found in [Khaiter 1991]. A sample view of FAIs from the perspectives of ecosystem critical conditions [Puzachenko 1989] and FEES anthropogenic dynamics [Khaiter 1991] is shown in Fig. 2.

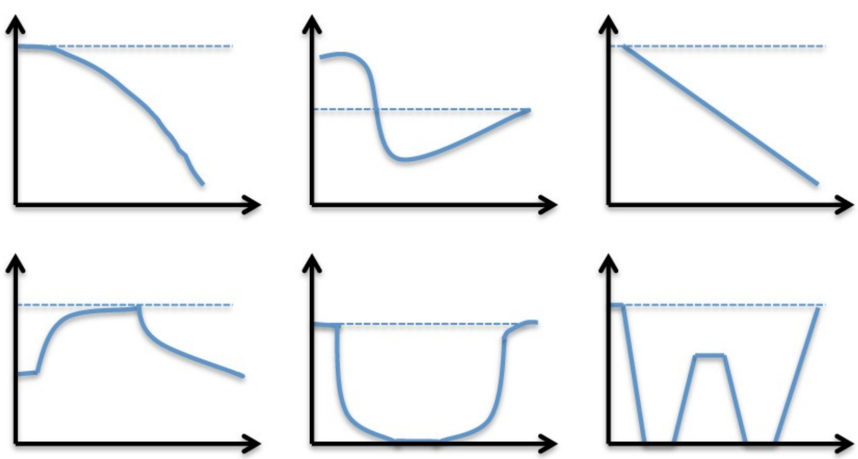

Figure 2 View of FAI [x-axis is time; y-axis represents coordinates of $\mathbf{x}(t)$].

5 CONCLUSION

Planetary role of forest ecosystems in carbon cycles and as carbon sinks, in particular, should be taken into the consideration when deciding on the scenarios of sustainable environmental management. Global forest resources assessment [FAO 2006] estimated the annual loss of 13 million hectares of forests caused by anthropogenic deforestation and natural factors, like forest fires. Global climate change coupled with other environmental problems calls to reverse this trend. Preservation of existing forests and regeneration (re-growth) of forests on previously deforested landscapes appear as valid alternatives of societal development, especially in view of the fact that forest service of carbon sequestration "often complements other environmental goals including protection of biologic, water, and soil resources" [Dixon et al. 1994]. Moreover, as noted [e.g. Fenshaw and Guymer 2009, Ngugi et al. 2011], there are emerging opportunities of carbon markets making forest preservation and restoration for biodiversity conservation and carbon accumulation purposes both environmentally and economically feasible. Any practical implementation of these management directions requires information on the quantitative values of ecosystem services that can be generated by forests under different management strategies.

ACKNOWLEDGMENTS

The authors are thankful to the three anonymous reviewers for their helpful suggestions and comments on the early version of the manuscript. Part of this work was supported by the Faculty LAPS Council through the individual grants to each co-author.

REFERENCES

Aber, J., R.P. Neilson, S. McNulty, D.B. Lenihan, and J. Drapek, Forest processes and global environmental change: predicting the effects of individual and multiple stressors, *BioScience*, *51*(9), 735-751, 2001.

Barett, G.W., and E.P. Odum, The twenty-first century. The world at carrying capacity, *BioScience*, *50*, 363-368, 2000.

Berg, B., and V. Meentemeyer, Litter quality in a north European transect versus carbon storage potential, *Plant and Soil*, *242*, 83-92, 2002.

Blanco, J.A., M.A. Zavala, J.B. Imbert, and F.J. Castillo, Sustainability of forest management practices: Evaluation through a simulation model of nutrient cycling, *For. Ecol. Manage*., 213, 209-228, 2005.

Costanza, R., and C. Folke, Valuing ecosystem services with efficiency, fairness, and sustainability as goals, *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press, 49-68, Washington D.C., 1997.

Dale, V.H., Managing forests as ecosystems: a success story or a challenge ahead? *Successes, limitations, and frontiers in ecosystem science*, Pace, M.L., and P.M. Groffman (Eds)., Springer, 50-68, New York, 1998.

Deckmyn, G., M. Campioli, B. Muys, and H. Kraigher, Simulating C cycles in forest soil: Including the active role of micro-organisms in the ANAFORE model, *Ecological modelling*, *222*, 1972-1985, 2011.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler, and J. Wisniewski, Carbon pools and flux of global forest ecosystems, *Science*, *263*(5144), 185-190, 1994.

FAO, *Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management*, Food and Agriculture Organization of the United Nations, 147 pp., Rome, 2006.

Fenshaw, R.J., and G.P. Guymer, Carbon accumulation through ecosystem recovery, *Environ. Sci. Policy*, *12*, 367-372, 2009.

Goodland, R., The concept of environmental sustainability, *Annual Review of Ecology and Systematics*, 26, 1-24, 1995.

Gorstko, A.B., and P.A. Khaiter, On the question of economic assessment of forest resources, Econ. Math. Meth. 27(3), 522-526, 1991.

Henschel, C., and T. Gray, *Forest carbon sequestration and avoided emissions*, IVEY foundation, 30 pp., Toronto, 2007.

Houghton, P.J., L.G. Meira-Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), *Climate change 1995: the science of climate change*, Cambridge University Press, 572 pp., New York, 1995.

Khaiter, P.A., *Modelling of anthropogenic dynamics of forest biogeocenoses*, Znaniye, 24 pp., Kiev, 1991.

Khaiter, P.A., Mathematical modeling in the study of the hydrological regime in 'Forest-Watershed' system, *Computational Methods in Water Resources*, Boulder, Colorado, CMP, 789-794, Southampton, UK, 1993.

Khaiter, P.A., Optimal control on the basis of a simulation system for environmental applications, *Numerical methods in engineering simulation*, 3rd Int. Cong. on Numerical methods in engineering and applied sciences, Mérido, Venezuela, February 1996, CMP, 297-302, Southampton, UK, 1996.

Khaiter, P.A., Valuing the ecological and socio-economic services in management of headwater ecosystems, *Hydrology, ecology and water resources in headwaters*, 6th Int. Conf. on headwater control, Bergen, Norway, June 2005, 1-10, 2005a.

Khaiter, P.A., Simulation modeling in quantifying ecosystem services and sustainable environmental management, *16th Int. Congress on Modeling and Simulation (MODSIM05)*. Modelling and Simulation Society of Australia and New Zealand, 347-353, Melbourne, Australia, 2005b.

Khaiter, P.A., and M.G. Erechtchoukova, Environmental assessment of anthropogenic impact through the patterns of ecosystem reactions, *The International Journal of Environmental, Cultural, Economic and Social Sustainability*, *3*(4), 181-190, 2007.

Khaiter, P.A., and M.G. Erechtchoukova, A Model-based quantitative assessment of ecosystem services in the scenarios of environmental management, *2010 International Congress on Environmental Modelling and Software, Fifth Biennial Meeting*, 5–8 July 2010, Ottawa, Canada, D. A. Swayne, Y. Wanhong, A. A. Voinov, A. Rizzoli, and T. Filatova (Eds.), 272-279, 2010.

Koerner, C., Slow in, rapid out-carbon flux studies and Kyoto targets, *Science*, *300*, 1242-1243, 2003.

Koo, K-A., B.C. Patten, and R.O. Teskey, Assessing environmental factors in red spruce (Picea rubens Sarg.) growth in the Great Smoky Mountains National Part,USA: From conceptual model, envirogram, to simulation model, *Ecological Modelling*, *222*, 824-834, 2011.

Kurz, W.A., and M.J. Apps, A 70-year retrospective analysis of carbon fluxes in the Canadian Forest Sector, *Ecological Applications*, *9*(2), 526-547, 1999.

Lindahl, B.O., A.F.S. Taylor, and R.D. Finlay, Defining nutritional constraints on carbon cycling in boreal forests – towards a less phytocentric perspective, *Plant and Soil*, 242, 123-135, 2002.

MA (Millennium Ecosystem Assessment), M. E. A., *Ecosystems and human well-being: synthesis*. Island Press, 160 pp., Washington, D.C., 2005.

Mueller, F., State-of-the-art in ecosystem theory, *Ecological Modelling*, *100*(1-3), 135-161, 1997.

Ngugi, M.R., R.W. Johnson, and W.J.F. McDonald, Restoration of ecosystems for biodiversity and carbon sequestration: simulating growth dynamics of brigalow vegetation communities in Australia, *Ecological Modelling*, 222, 785-794, 2011.

Odum, E.P., *Basic ecology*, Saunders College Publishing, 402 pp., Philadelphia, 1983.

Potter, C., J. Bubier, P. Crill, and P. Lafleur, Ecosystem modelling of methane and carbon dioxide fluxes for boreal forest sites, *Can. J. For. Res*., *31*, 208-223, 2001.

Pregitzer, K.S., and E. Euskirchen, Carbon cycling and storage in world forests: biome patterns related to forest age, *Global Change Biology*, *10*, 2052-2077, 2004.

Puzachenko, Yu.G., (Ed.), *Ecosystems in critical conditions*, Nauka, 155 pp., Moscow, 1989.

Roulet, N.T., Peatlands, carbon storage, greenhouse gases and the Kyoto Protocol: prospects and significance for Canada, *Wetland*, 20(4), 605-615, 2000.

Scheller, R.M., D. Hua, P.V. Bolstad, R.A. Birdsey, and D.J. Mladenoff, The effect of forest harvest intensity in combination with wind disturbance on carbon dynamics in Lake States Mesic Forests, *Ecological Modeling*, *222*, 144-153, 2011.

von Bertalanffy, L., *General systems theory: foundations, development, applications*, G. Braziller, 289 pp., New York, 1969.