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Towards conceptual tool differentiation in the sustainability discussion:
Critical Loads and Sustainable Development of Siberian Forests

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Contents

Foreword

IIASA's Sustainable Boreal Forest Resources project has managed, in cooperation with Russian collaborators, to build a comprehensive database on emissions of pollutants in Siberia and Russia.

The objective of this paper is to try to investigate the possibilities to continue the Siberian pollution database analysis., The author uses the critical loads concept to see if this approach could serve as an indicator for the sustainable development concept. This report deals with some of the theoretical backgrounds for a more quantitative example, which is prepared in a second paper.

The work has been carried out by Mrs. Koko Warner-Merl during her stay as a guest scholar at the institute during 1997 and 1998.

Abstract

In the wider debate about the environmental sustainability of various human activities, the literature lacks a specific link between the discussion and the use of differentiated analytical tools for conceptualizing and measuring sustainable development. This paper explores a key issue in the sustainability debate: developing differentiated analytical tools to define and apply the concept of sustainability. This work seeks to build a theoretical bridge between the root concept of sustainable development and a new concept, critical loads, which both defines and measures the *unsustainability* of certain anthropogenic activities. The development of the sustainability concept is briefly reviewed, followed by a discussion of the difficulty of applying this concept due to definitional problems. The author argues that by using concepts which make explicit the relationships between anthropogenic activities and environmental degradation, policy makers can better apply the concept of sustainable development. The author assesses the critical loads concept as a way for policy makers to assess differentiated levels of unsustainability. To illustrate this, the author explores the use of the critical loads concept to assess environmental degradation in Siberia, which is currently being used to contribute to a sustainable development policy for the region.[1] Moving from a dichotomous, relatively static view of human-environment interactions to one which captures varying degrees of these interactions reveals greater insights about the political, economic, and physical relationship between nature and its most influential species, *Homo sapiens.*

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[1] This report is written in conjunction with an IIASA research fellowship on sustainable boreal forest resources, which the author received for the summer of 1997. The project aims to add a quantitative input to a sustainable development concept for the boreal forest zone in Russia, and to provide an analysis of the data which may help policy makers identify a portfolio of policy options for the region. Using the critical loads concept, the author will assess the status of the Siberian region, and analyze the risks and impacts of anthropogenic pollution on the environment and its life forms there. This work provides the theoretical support for the research work on boreal forest resources.

1. Introduction

The concept of sustainable development has captured the attention of policy makers and scholars as anthropogenic (human-caused) forces have accelerated the degree of environmental change at local, regional, and global levels (WCED, 1987). The negative effects of these environmental changes have brought research on the consequences of human activities on the environment to the fore, with a central debate currently centering on creating policy for the sustainable use of land, water, air, and other natural resources (Bartelmus, 1994). Although much has been written about global issues of sustainable development, the discussion lacks systematic studies of the risks and impacts of anthropogenic factors influencing the sustainability of particular types of environmental areas. A possible reason for this blank spot in academic and applied circles is the scarcity of appropriate tools of analysis which can grasp the complexity of environmental-human interactions and which can estimate with some certainty the level of human-related stress on a given ecosystem. A major critique of environmentalists and economists alike has been the fact that in spite of intense international attention, the root concept of sustainable development remains useless without specific tools of measurement and conceptualization of various conflicts between human use and environmental degradation. Developing more differentiated[2] tools of analysis is the most important task for social and natural scientists as they try to provide policy makers with the best possible methods to evaluate the environmental risks and impacts of anthropogenic activities (Suter, 1993) [3]

Before policy makers can meaningfully analyze patterns of anthropogenic activities, they must first have access to differentiated tools which allow them to measure the relationship between environmental degradation and human activity (King *et al.*, 1994). This progress towards conceptual differentiation is necessary for correct measurement of the environmental-economic development trade-offs which must be negotiated in particular regions and are vital for the formation of appropriate policy.

Showing explicitly the value of using such a differentiated measurement concept enables researchers to make concrete progress towards methods and tools for assessment of sustainable development. The development of such tools plays a key role in the sustainability debate, which tries to find ways for humans to make economic and social progress in the present, using the natural resources available to them without compromising the needs of future generations (Foster, 1997).

While the discussion of improving tools for measuring sustainable development has been widely debated, it is necessary to make these improvements explicit. The more information and the higher certainty which different tools of data analysis yield, the

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[2] By differentiated, the author means that these tools achieve analysis at various levels, scales, intensities and concentrations, and over time and space. Such tools can add insight into complex environmental-human interactions.

[3] An analysis of patterns of anthropogenic activities will yield estimates of how sustainable human-environment interactions in a given region are. This could lead to more certain estimates of necessary adjustments in these activities to produce a sustainable environment management policy. This analysis can then be used to define possible future land use and ecosystem changes in specified regions under different assumptions of future demographic, political, technological, and economic and social conditions. See Glenn W. Suter II (ed.), *Ecological Risk Assessment* (London: Lewis Publishers, 1993), 44-49.

better policy makers and scholars can devote their efforts and budgets to striking a truly sustainable balance between economic development and environmental integrity. Because of the enormous monetary resources involved, the political sensitivity of many issues surrounding the use of natural resources, and the pressing need to find solutions to some of the most pressing environmental problems, tools need to be as specific as possible and measure with the greatest amount of certainty the risks and impacts of human activity upon the environment.[4]

1.1 Objective and Relevance

As an illustrative example of how differentiated tools can help policy makers make appropriate decisions about development in the face of limited and not-always-robust natural life-support systems, the author poses a case study of atmospheric emissions in Siberia. First, the author introduces the root concept of sustainability, noting some of its weaknesses. Second, she argues for the development of differentiated (graded concepts) tools to overcome the shortcomings of the root concept. Third, the author explains by example of the critical loads concept how these differentiated tools could work within the international sustainable development discussion. Critical loads promises to facilitate international abatement of harmful emissions. This is a powerful example of how differentiated analytical tools make sustainability more accessible and applicable to policy makers. For example, the critical load concept can yield some of the following findings for the creation of more sustainable development policies:

- Make explicit how anthropogenic factors affect the spatial characteristics, temporal dynamics, and environmental consequences of land use and ecosystem changes in a given area.
- Estimate the sustainability of current human activities in a region by assigning threshold values and target loads to pollutants, which can lead to better estimates of necessary adjustments in these activities to produce a sustainable natural resource management policy.
- Calculate future environmental changes in specified sub-regions under different assumptions of demographic, economic, political and social conditions.

2. The emergence of a sustainability concept

The term "sustainability" became popular after its introduction by ecologists and economists who were trying to find a conceptual container to capture the idea that economic development must not sacrifice long-term resources upon which it depends. During the first ten years of its existence, the United Nations Environment Program (UNEP) attempted to define a terminology that would push beyond what had been up

[4] One unexpected observation which leads to this study is that initial data have shown higher-than-expected levels of pollution within the Siberian region. A study of this phenomena is worthwhile and may help scholars and policy makers better understand the complex relationship between human activities and the environment. The author proposes using the critical load concept to evaluate the status of the environment in Siberia and analyze patterns which emerge from that evaluation. By using this method, which is sensitive not only to ecoregion type but also provides five different levels of "criticality," the findings of this research will add much more insight to the efforts of policy makers to develop a sustainable development program in Siberia than by using other tools.

until then rather simplistic, “either-or” trade-offs and implications of the environment-development nexus (Tryzna, 1995). Moving from a realization that problems existed between development and environmental integrity, the idea took form without attachment to measurement tools. Tryzna (1995) notes, “In the beginning there was not even much expectation to operationalize the concept it was simply a question of trying to define some kind of a process that would lead to a better world and a better path of development.” Relatively soon after the IUCN formulated the World Conservation Strategy which highlighted sustainability (IUCN/UNEP/WWF 1980), the concept took on a concrete focus on time and continuity, which in turn made space for a range of quantitative and qualitative issues such as distribution and equity, efficiency, intergenerational welfare, and resource management. Yet it lacked an operational definition which could allow measurement. Pearce *et al*. (1990) notes, “While ‘sustainable development’ is the acknowledged subject of much recent development thinking (WCED, 1987, Repetto 1986, Redclift 1987, Turner 1988, Stockholm Group 1988), little headway appears to have been made in terms of a rigorous definition of the concept. Therefore, not surprisingly, efforts to ‘operationalize’ sustainable development and to show how it can be integrated into practical decision-making have been few and generally unpersuasive.” One researcher wrote that he was convinced that “sustainable development” was “ambiguous, unhelpful, and ill-defined as ever, that it is not supported by a concrete body of theory, and means all things to all people.”(Tyrzna, 1995). Other similar criticisms abound.

In spite of current concern, the sustainable development concept has enormous potential to guide policy makers in defining future possibilities for human-environment interaction. What is needed, and what much current research has revealed, are analytical tools which focus upon specific subsets of human-environment interaction and which give policy makers clear options for pursuing the root concept of sustainable development.[5] Such tools ideally make it clear what problem is being dealt with, what is being measured, the sources of the problem, and levels at which human activities do *not* lead to unrepairable environmental change.

Principle 1 of the Bellagio Principles (International Institute for Sustainable Development, 1996) states, “Assessment of progress toward sustainable development should be guided by a clear vision of sustainable development goals that define that vision.” The paradox we face, however, is that the root concept of sustainablity—regardless of the weight it carries or its appropriateness to present discussion of human use of the earth—is difficult to define and measure.[6] However, a general understanding and agreement about the root concept has emerged, making it possible to develop more differentiated analytical tools to measure progress towards it. The conclusions of an international workshop in Ghent in 1995 state:

[5] Scholars have increasingly come to realize that a dichotomous approach to environmental-human activity interaction evaluation (i.e. polluted/non-polluted) was inappropriate. Dissecting environmental/human interaction in this way manifested the danger of lumping together dissimilar cases, or overlooking important variances within cases which had importance for the development of area-specific sustainable development policy.

[6] There are many definitions of sustainable development but no consensus on one single definition.

> The potential uses of [such tools] include alerting decision-makers to priority issues, guiding policy formulation, simplifying and improving communication, and fostering a common understanding of key trends with a view to initiating necessary national action. The primary focus and purpose of [these analytical tools] is to facilitate decision-making at the national level. They should be considered as useful tools that countries can decide to use as sources of information on progress towards their own targets for sustainable development (Moldan and Bilharz, 1997).

In addition, the very process of developing such tools-- also called indicators of sustainable development in the international discussions (UNEP, 1995) contributes to the creation of a better definition of sustainable development. As Moldan and Billharz (1997) state, “These processes are parallel and complementary: working on indicators helps us to see the important processes and linkages among aspects of sustainable development at many levels and to appreciate fully the complex interactions among its different dimensions.” Rather than analyzing sustainability in a bifocal way, developing analytical concepts which allow policy makers to see the multilevel balance between environment and people and the amount and extent of imbalances leads to more appropriate and effective policy (Moldan and Bilharz, 1997). As Arthur Dahl (1996) points out,

> sustainability is fundamentally a question of balance maintained over time-- it is a quality of motion rather than a fixed point. It may be more easily defined, in practice, as the lack of forces tending to upset an equilibrium over time. This is why most indicators are, in fact, measures of unsustainability, i.e. the amount or extent of imbalances. As with a moving pendulum or an aircraft in flight, many different forces can act simultaneously to disturb an equilibrium. The challenge for developing [concepts for measurement] of sustainability is to find simple ways of presenting the idea, despite the complexity and uncertainty.

The nature of the problem—analyzing complex relationships with high degrees of uncertainty—is best seen through differentiated tools which, although diverse and often problem-specific (such as air pollution) can provide much clearer focus on the root concept of sustainable development. Among a growing array of such tools, the critical loads concept (Chadwick and Kuylenstierna, 1990) provides a versatile and relatively clear way of presenting complex interactions between the environment and human-caused pollutants.

3. Conceptual tools and the sustainable development debate

Sustainability lies on a continuum rather than a dichotomy. Therefore, tools to measure and serve as indicators for sustainable development should also lie on a highly differentiated continuum. The study of human-environment interaction demands tools that offer the policy maker a high degree of resolution into complex situations. Stressing the need to develop differentiated tools, Moldan (1997) states,

> [tools] must be comprehensive enough to take into account: stresses on economies, ecosystems, and social fabrics; impacts of stresses on the present state of complex systems; and responses to these stresses. Within various contexts, indicators are needed to clearly show whether we are on the right track and in what direction we are headed.

Dichotomous measures of many problems have served as a way for policy makers to efficiently categorize ideas. However, due to the special nature of environmental problems (decision making and game theory, transboundary elements, heterogeneous, complex chemical processes, high costs which are difficult to collect from the beneficiaries), dichotomous analytical tools are of little value for problem-solving policy makers. To underscore this trend, one author noted the "need to develop indicators that can communicate complex findings on the conditions, trends, and impacts in important environmental sectors to policy-makers, as well as to the public, so that they can act or demand actions." (Rodenburg, 1995).

Recognizing the need for tools that could capture the complex issues surrounding current discussions, researchers began focusing on indicators and new methodologies. Winograd (1997) has written:

> It is evident that diverse approaches, perspectives, needs and uses exist in relation to sustainablity and to indicators of the development process. If diversity is one of the key characteristics or attributes of sustainability, then indicators can no longer be produced and simplified into simple indices. It appears more realistic and pragmatic to produce and use indicator tools to measure and analyze the whole pattern shown by the development process. In order for this to happen, indicator lists, aggregations or summations are needed, *along with information that incorporates different scales, levels and components.*

In 1996 the Scientific Workshop on Sustainable Development Indicators (Wuppertal, Germany) identified several areas in need of further research to allow the sustainability discussion to continue meaningfully. Their conclusions underscored the need for differentiated analytical tools in the sustainable development discussion. The group indicated that development and research were needed in environmental indicators such as stock measures, source indicators, and geobiosphere load indicators (Moldan and Bilharz, 1997). The future path for the sustainability discussion lies in developing differentiated conceptual tools which can yield deeper insights across a variety of fields.

Although the root concept of sustainable development sets out principles for identifying non-environmentally sustainable activities, in itself it cannot readily identify such areas or activities. To enhance the ability of the concept to work as a force for global environmental integrity in the face of economic development, policy makers and researchers need the differentiated tools created to meet this demand in the past two decades. Tools such as the critical loads concept allow policy makers and scientists to identify areas of acute environmental risk, as well as assess the degree of risk which these areas display. Using such differentiated tools then allows policy makers to identify causes of environmental degradation and formulate more appropriate policy to allow (ideally) both economic development and environmental sustainability.

4. The Critical Load Concept

The critical load concept bases its analysis on the assumption that, every ecosystem, whether terrestrial or aquatic, has only a limited capacity to cope with anthropogenic pressure, in this case pollution, without experiencing unacceptable damage to flora and/or fauna (Bakker and de Vries, 1996). Developed in 1986 by Nilsson, the critical loads concept combines data collected by natural scientists about the deposition of air pollutants and appropriate levels of pollution in order to prevent environmental damage.[7] A UN/ECE working Group defined the critical load for an ecosystem as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge (Nilsson and Grennfelt, 1988)." In other words, a critical load for any given ecosystem is the maximal exposure to an anthropogenic activity (in current usage, pollution) that an ecosystem can adjust to without suffering long term damage. In the international discussion of acid rain, for example, soil acidification depositions above the critical load first lead to reversible damage of the soil and then to irreversible damage. Although it is costly in the present to reduce atmospheric emissions which lead to acidification, higher stocks of pollutants over time reduce soil productivity and possibly ultimately destroy production capacity all together. Dynamic cost-benefit analysis implies that in the long run, depositions of identified pollutants cannot exceed the critical load if human use of natural resources in a region is to be sustainable. Thus, using the critical load concept to assess the current and future sustainability of anthropogenic activities attaches a normative meaning as well as defines sustainability for a specific environmental problem (Maler and de Zeeuw, 1995). The critical load concept is introduced to achieve a maximum benefit of emission reductions at lowest costs, as an alternative to the use of e.g. technical abatement measures.

The concept is useful within the larger sustainable development discussion. While it can be used for a variety of different aspects of the sustainablity debate, critical loads is designed for assessment of atmospheric emissions and transboundary air pollution. The conceptual tool is flexible enough for use with different ecosystems and for different chemical compounds, although most initial work has focused on sulfates and nitrates. Current efforts to apply critical loads to heavy metals and persistent organic pollutants (POPs) will expand the ability for policy makers to define sustainable human activities.

4.1 A theoretical bridge between critical loads and sustainable development

The critical loads concept has a stock and flows feature which makes it clear to policy makers that in a steady state depositions of harmful pollutants cannot exceed the

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[7] For example, the algorithm for computer calculations of critical load of nutrient nitrogen ($CL_{nutr}N$) in Russia has been based on the following equation: $CL_{nutr}(N) = {}^{\alpha}N_u + {}^{\alpha}N_i + {}^{\alpha}N_{de} + {}^{\alpha}N_{1(crit)]}$, where $^{\alpha}$ means that each of the terms refers to the values at the actual total atmospheric precipitation at the side. N_u and N_i are permissible nitrogen uptake and soil immobilization, N_{de} is permissible denitrification and $N_{1(crit)]}$ is the permissible critical nitrogen leaching. See V.N. Bashkin, V.V. Snakin, and M. Kozlov *et al.*, in R.J. Downing, J.P. Hettelingh, and P.A.M. de Smet (eds.), *Calculation and Mapping of Critical Loads in Europe: States Report 1993* (RIVM, 1993), 102-122.

defined critical load threshold. The flow aspect refers to the level of flow pollution an ecological system can adjust to without suffering any damage. Depositions above this critical load give rise to accumulation pollution in response to which chemical changes in the environment occur. At such levels, the stock of pollutants indicates how much damage is done to the ecological system. Also at levels above critical loads, the stock of pollution imposes irreversible damage to the natural system, or leads to the break down of the life support function of the ecological system. In the case of acid rain, this point is where forests die, fish and water systems are poisoned and die, and/or the natural resource base is fully depleted (clearly not optimal). Exceeding critical loads by continuing unsustainable anthropogenic activities leads to a situation of irreversible damage and, over time, to a break down of the life support system (de Vries, 1988).[8]

Critical loads make sustainable development more operational in specific contexts. Critical loads and the methodologies associated with the tool provide policy makers and researchers a way to handle some of the most problematic themes within the concept of sustainable development (Adams and Adams, 1987). These points of conflict—such as defining and making policy for intergenerational welfare and natural capital stock, and discount rates -- indicate the importance of using differentiated tools of analysis when attempting to measure sustainability. Because the concept gives rank and order to situations of environmental risk by identifying areas where thresholds for critical loads are exceeded, the concept allows for a range of discussion on issues such as the impact of pollutants on biodiversity, pollution measurement, climate change, and human welfare and consumption patterns.

4.2 Intergenerational welfare and natural capital stock.

Based on the WCED definition for sustainable development, future generations should have access to at least the same level of environmental products (in the form of life-support and waste recycling systems, quality of life, and natural resources) as the present one. Not only have researchers and policy makers had difficulty in defining what activities compromise intergenerational welfare, they have also found it difficult to identify levels at which identified activities are acceptable and at which they are not. Rawl's theory of social justice—the idea that a bias should exist in resource allocation towards the least well-off member of society—suggests that anthropogenic activities which harm the environment should be limited at the lowest possible level to avoid impacts upon the most vulnerable (Rawls, 1972).[9] The concept of critical loads helps policy makers define intergenerational welfare by demonstrating with some accuracy at what levels the environmental begins to change as a result of anthropogenic pollutants. Critical loads calculation reveals a spatial pattern of pollutant deposition The approach can be used to note intragenerational welfare if certain members of society are more

[8] For example, soil microorganisms and soil fauna responsible for decomposition processes in the soil (e.g. decreased biodiversity), vascular plants including crops in agricultural soils and trees in forest soils (e.g. production loss), terrestrial fauna such as birds and humans that consume crops or drinking water contaminated with pollutants (e.g. excess of acceptable daily intake, causing toxic effects). In aquatic ecosystems, a distinction can be made in aquatic and benthic organisms or humans that consume fish or drinking water contaminated with pollutants. See deVries, 16.

[9] Rawl's argument was set in the context of welfare for developing economies. Although not foreseen for the sustainability debate, his argument provides a moral basis for arguing that future generations should have at least as much access to the natural resource base at those in the present. J. Rawls. *A Theory of Justice* (Oxford: Oxford University Press, 1972).

exposed to atmospheric emissions than others. It can also be used for intergenerational welfare policy by informing decision makers at what levels environmental degradation will become irreversible. This in turn can be used to "control" how far degeneration goes before the welfare of future generations is compromised.

According to the implicit assumption in the Brundtland report, sustainable development will not depreciate natural capital stock. The report states, "If needs are to be met on a sustainable basis the Earth's natural resource base must be conserved and enhanced" (WCED, 1987). Repetto (1986) advocates a similar definition, "sustainable development is a development strategy that manages all assets, natural resources and human resources "for increasing long-term wealth and well-being. Sustainable development, as a goal *rejects policies and practices that support current living standards by depleting the productive base, including natural resources*, and that leaves future generations with poorer prospects and greater risks than their own."

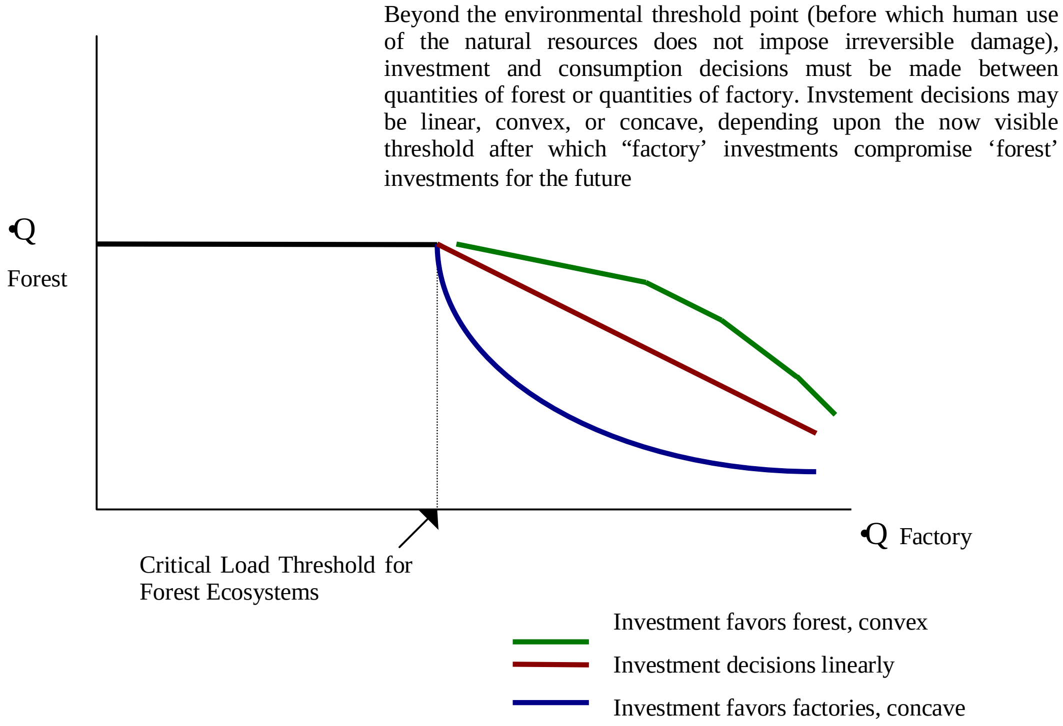
Natural capital stock should not decrease over time. But measuring the decrease of natural capital is problematic and it is often unclear at what point irreparable deterioration occurs. With reliable data on ecosystems, however, calculating critical loads provides a tool for measuring decrease or the beginning stages of degradation. Once critical loads are assessed for particular ecosystem and soil types, policy makers can set target loads for pollutants with the goal to reduce natural capital stock deterioration. Critical load clearly defines the levels of emissions at which chemical changes do not occur in the biosphere. Based on various social factors such as economics, politics, legal system, etc., policy makers can then formulate goals to maintain or augment the natural capital stock.

4.3 Discount rates

Discount rates are a mechanism by which one can compare the value of economic resources and services at different points in time. The concept behind discount rates is that a certain resource utilized today has a higher value than the same resource used at some future point. The percentage by which policy makers reduce income flows between two temporal points is called the discount rate. Usually applied to the consumption of natural resources or to evaluate investment decisions, discount rates are also relevant for the international abatement discussion. Pollution "consumes" natural goods by reducing their ability to reproduce, by making them unusable or unavailable for people, or by changing the life-supporting balances upon which people depend for other productive activities.

Rather than assigning a monetary value to environmental goods, the critical loads concept provides another way to measure and possibly prevent overconsumption of present natural resources. Instead of discounting the future, critical loads concept provides an environment-based limit system that indicates beyond which point of present consumption irreparable damage will take place. This irreparable damage represents the point at which the possible future consumption of a natural good has been diminished. The discount rate at the highest level of exceedances represents the point at which use of the environment (in this case industrial pollution of Siberian ecosystems) has become unsustainable. Each level of exceedance could represent one level of discount rate for present consumption.

Box 4.3 Using Critical Loads to define “forest” and “factory” investment scenarios



Although the critical loads concept does not apply appropriate discount rates to particular biospheres, it can provide a way for policy makers to assess investment rates for specific ecoproducts. Investment in consumption (pollution) today manifests a preference for the present time period over that in the future (the discount rate is effective and positive). Appraisal of the resource and the environmental consequences of present consumption (e.g. atmospheric emissions) must be made for proper decisions about the use of those resources (e.g. investment decisions). Efforts should be made to measure environmental damage, which critical load thresholds and recorded exceedances, combined with remote sensing imagery, can indicate. Using its estimates of threshold values, researchers can approximate the rate of degradation to particular endpoints (such as particular species of fish, trees, microorganisms, as well as threats to human health by unsuitably high levels of air pollution) and better determine monetary prices or opportunity costs of the atmospheric emissions. Because monetary values are often attached to the victims of pollution, calculating critical loads and the impacts of atmospheric emissions on objects such as trees (such as needle loss and die back) allows policy makers to more accurately determine investment decisions (present vs. future consumption) under the existing discount rates. By demonstrating the economic value or importance of natural environments and natural resources, critical load estimations make more clear what levels of present consumption are acceptable and sustainable.

For the present example of critical loads in Siberia, the concept can help define sustainable development possibilities for several sectors, particularly forestry. Forestry provides a major economic engine for the entire region, and will increase in importance as other world resources for wood products decrease. Forestry has longer time horizons than many production sectors. Therefore, forest damage from factory emissions today (a form of consumption of industrial production) can mean long-term profit loss for the industry. Critical loads calculate the environmental threshold beyond which such natural resources will experience irreparable damage. Policy makers have a strong interest in preserving forest quality (natural stock), ensuring that the resources are available for future economic development (intergenerational welfare), and formulating policy which will assess the damage done now and in the future to the forest base by pollution.

The tool makes explicit the present trade-off between consumption levels (measured in terms of emissions and depositions of toxic substances) and depletion of natural resources. Using discount rates to appraise investment alternatives, decision makers can assess if they are willing to accept convex, linear, or concave relationships between "factory" production which after the point defined by critical loads compromises "forest" production (a proxy for natural resources). Studies of critical loads for nitrogen and sulfates, heavy metals and organic substances, discussed below, will help policy makers assign a sustainable development path for the region.

5. Application of critical loads

One prominent debate in the trade-off between development and the environment centers on pollution, or toxic atmospheric emissions (Mabey *et al.*, 1997). Such emissions are primary or secondary products of many activities associated with industrial development and production such as smoke emissions from factories, or from increased levels of economic well being reflected in higher use of automobiles and other petroleum-utilizing processes (Koutrakis and Sioutas, 1990). In a quest to develop, the natural consequences in the form of higher pollutant depositions have begun to compromise environmental integrity. In some areas, the situation has progressed to the point where economic activities are sometimes impeded as the natural base upon which they depend is no longer available.

It has become clear that pollution-causing human activities compromise the environment, but a tool was necessary to measure the impacts and risks both for future economic activities associated with pollution and for the survival of natural resources. Concern about acidification, ozone, and negative health impacts resulting from heavy metals have brought the critical load concept into wider use. Using this tool, policy makers can identify areas where the environment cannot recover from anthropogenic stress or where natural resources are depleted in a way that compromises their future availability. For example, acidification has become an international concern because depositions of sulfur and nitrate oxides (two acidifying compounds) exceed the critical loads in many countries, causing damage to ecosystems, buildings, and human health.

The section below briefly outlines the environmental problems posed by acid rain and places the issue within the sustainability discussion. Critical loads provide a way to measure environmental impact of atmospheric emissions and allow policy makers to set target loads for the reduction of emissions. The approach could also be instrumental in supporting legislation to reduce emissions-related environmental damage.[10]

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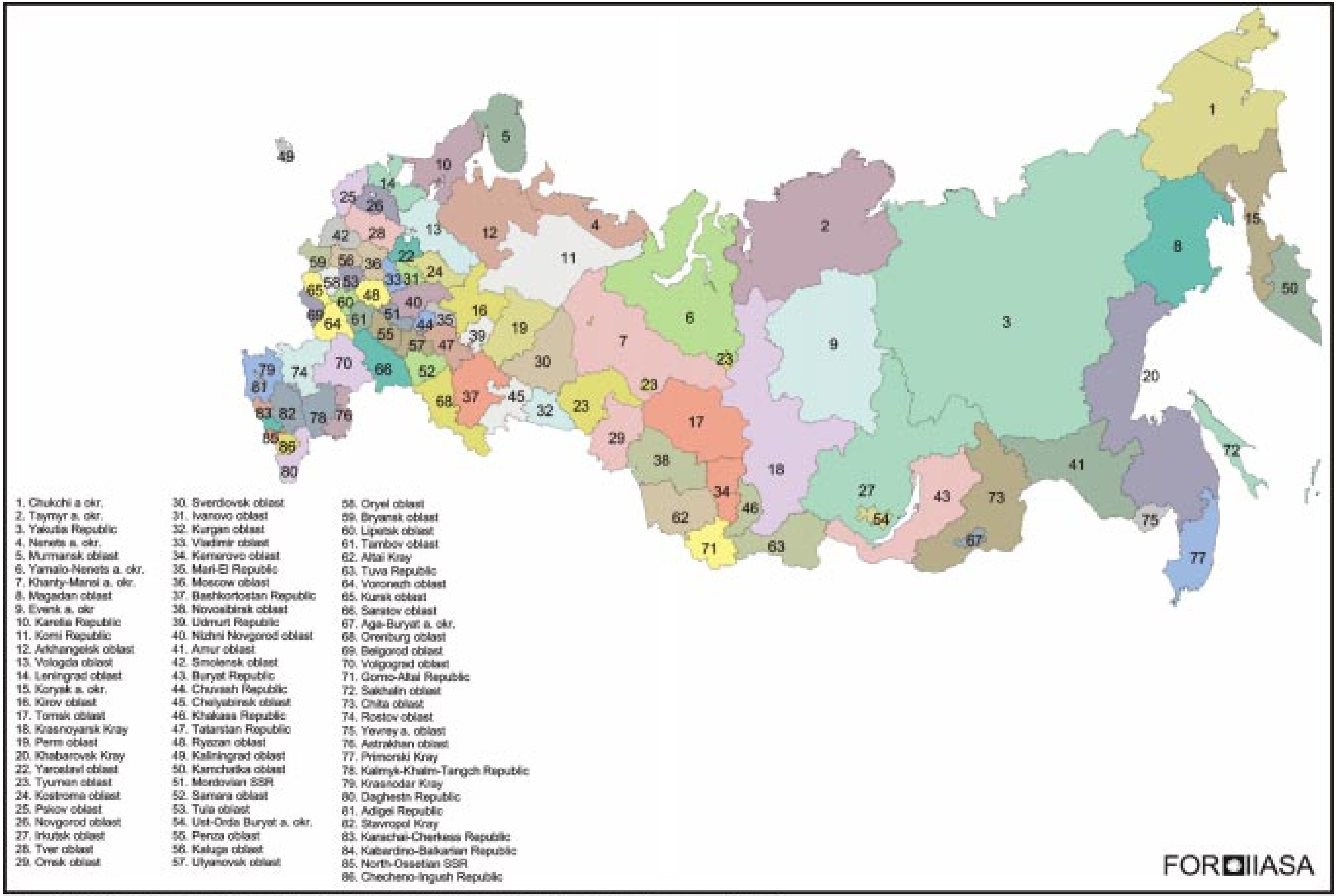
[10] See, for example, the 1990 Federal Clean Air Act Amendments (U.S.) which require power plants across the nation to reduce sulfur dioxide and nitrogen oxide emissions. The amendments also impose tougher emissions standards for passenger cars and light duty trucks. These measures will reduce significantly the pollutants that contribute to acid depositions.

Acid depositions occur as atmospheric pollutants fall from the air. Principle sources include smokestacks of fossil fuel power plants, other industrial facilities and automotive exhausts. These emissions contain sulfur dioxide (SO_2), the major contributor to the problem, and nitrogen oxide (NO_X). These gases combine with oxygen and water vapor in the air to form sulfuric and nitric acids. The acids fall to the earth in two forms of deposition. When precipitation such as rain, sleet or snow containing dissolved sulfuric or nitric acid falls to the ground, it is termed wet deposition or "acid rain." If the acids descend as sulfate or nitrate particles, it is labeled dry deposition.

Acid depositions create transboundary air pollution problems as wind transports them potentially hundreds of miles from the source. In addition, emissions are unevenly distributed, as clearly seen in the example of Siberia. Acid depositions can cause problems in almost every aspect of the environment. Upsetting the pH balance in water systems, organisms ranging from fish and amphibians to microorganisms lose reproductive capabilities. In forested areas such as Siberia, sulfates and nitrates can contribute to tree die-back and needle loss. Researchers and policy makers have increasingly used critical loads to assess the levels of pollutants deposited in the system by atmospheric emissions. After calculating critical loads, target loads (which take into consideration possible legal, technical, ecological, economic, and political concerns) can then be set to form the basis for negotiating acceptable emissions reduction strategies (Nilsson, 1991).

5.1 Assessing critical loads of sulfates and nitrates in Siberia

Determining critical loads and exceedance yields a picture of the overall pollution situation of a region. In turn, this picture can allow one to make inferences about the balance between human activities and the environment. Published in 1991, the first European maps of critical loads enhanced policy-making activities relevant to emissions abatement, noting regions where nitrates and sulfates exceeded threshold values (Downing *et al.*, 1993). Because long-range transboundary air pollution is a not confined to areas of the immediate source of emissions, applying the critical loads methodology helps researchers and policy makers determine the degree to which particular ecosystems are threatened from atmospheric emissions. The approach allows analysis of pollution profiles of large areas which may incur damage from such chemicals. The approach was applied in Northern Asian (an area including Siberia) by Bashkin *et al.* (1995). Combined with current research at the International Institute for Applied Systems Analysis, their research will contribute to the formation of of a sustainable development policy for Siberia. Map 5.1, a political map noting the names of the administrative regions of the Russian Federation, serves as a general geographical guide for the ensuing discussion of the distribution of critical load thresholds and exceedances, according to recent studies by Bashkin *et al.* (1995) and Nilsson *et al.* (1996).



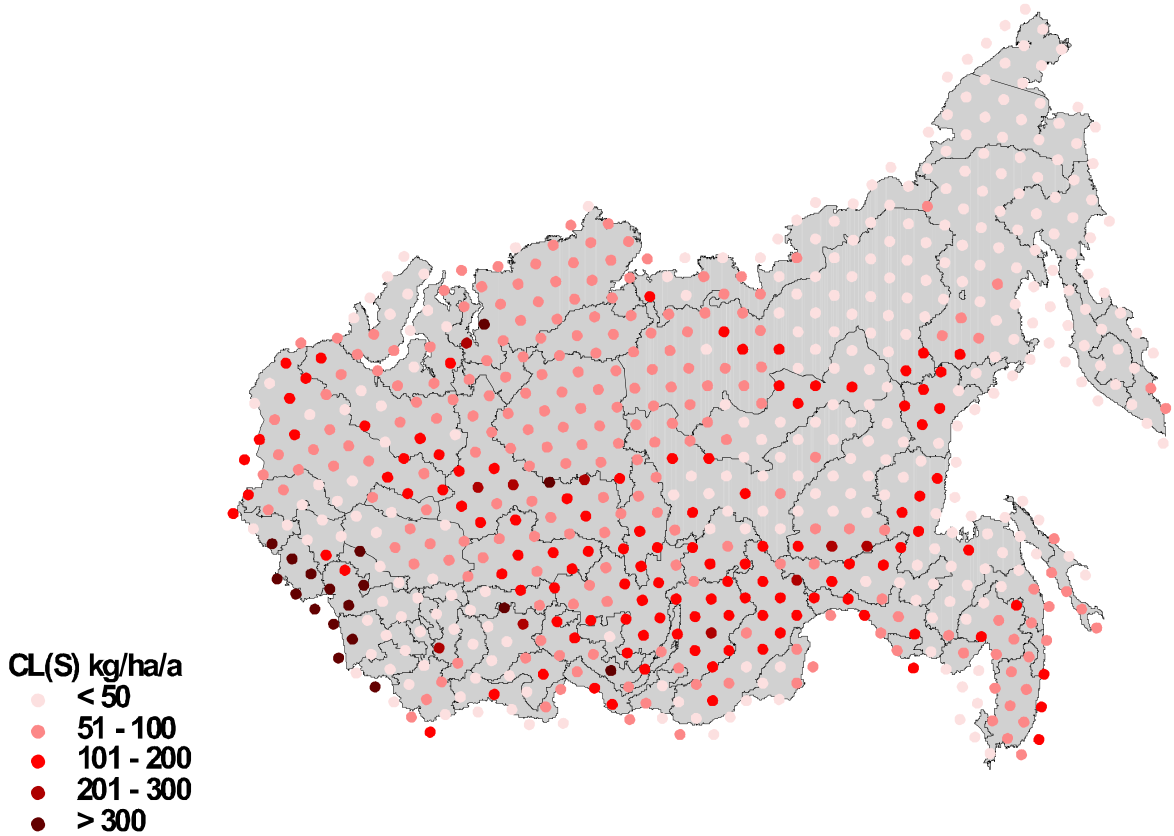
Map 5.1 Political Map of the Russian Federation (Source: IIASA, Sustainable Boreal Forest Resources Project)

An advantage of the critical loads tool is that it reveals clear exceedance patterns of pollutant deposition in Siberia, which correlate with anthropogenic activities in the region. Due to the characteristics of many ecosystems in Siberia, although the absolute levels of pollution may be lower than for Europe or South Asia, these areas may also be more sensitive to atmospheric pollution. That is, pollution levels may be lower, but the environmental thresholds for pollution may also be lower. In these areas less robust ecosystems are more sensitive to emissions. Such findings reveal the necessity for a development policy that treats such areas according to their environmental sensitivity. Bashkin *et al.* (1995) showed that the arctic and subarctic ecosystems of Northern Asia manifested minimal values of critical loads of nitrates (<50 eq/ha/yr). The typical critical load values for the majority of the ecosystems in the permafrost area lay within limits of 50-100 eq/ha/yr for nitrates in the same region. These ecosystems are very sensitive to the excessive input of “technogenic” nitrates. The maximal values of nitrate critical loads, >300 eq/ha/yr, were noted for ecosystems of chernozemic and chernozem-like soils of the southern regions of Siberia and the Far East.

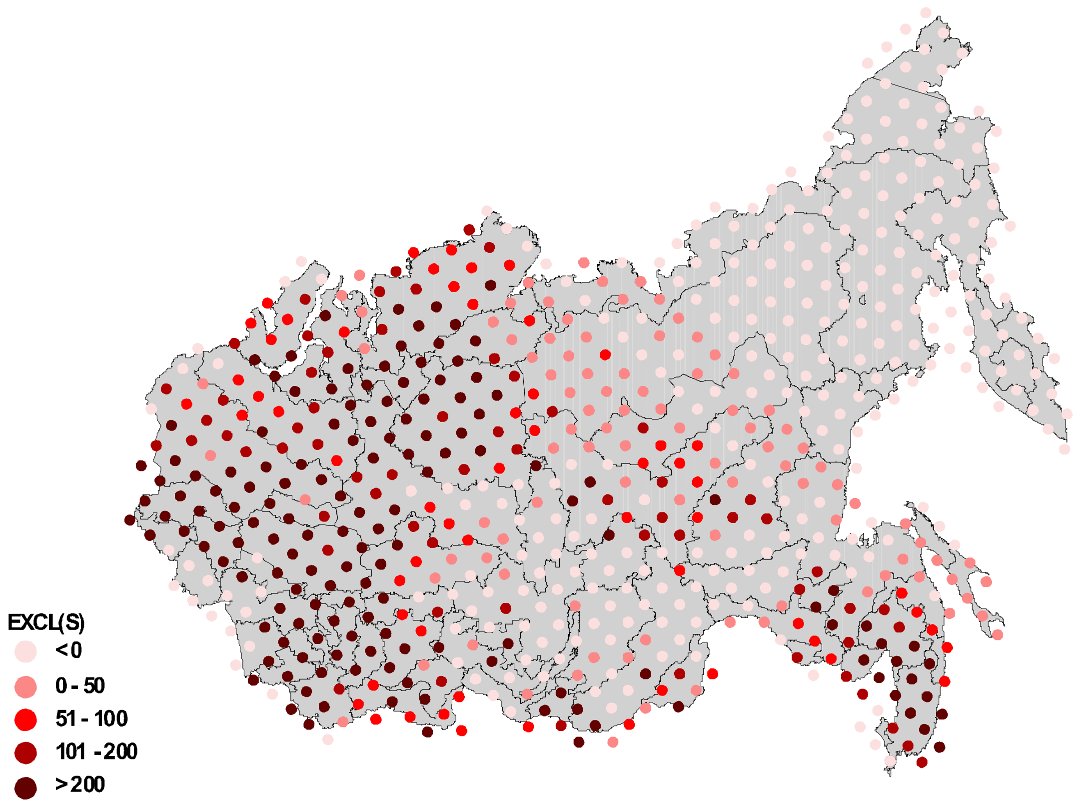
As an example of varying carrying capacities, Map 5.2 illustrates the spatial distribution of defined critical loads of sulphur for Siberian ecosystems. Areas most tolerant of pollution are clustered in the western parts of the Russian Federation, while large parts of Siberia manifest much lower critical load thresholds. The first category, <50 kg/ha/yr is an indicator that areas thus marked have lower tolerance, or lower critical loads for given pollutants. The western border of Siberia manifests higher critical load values for sulfur, for example, than does the eastern half of the region, which measures in the lowest category. The five different levels represent according to ecosystem data the loads under which the environment will not experience irreversible chemical change. Such a tool allows for more insightful policy as decision makers take into consideration not only economic criteria, but environmental ones as well.

When emissions exceed the carrying capacity of a given ecosystem, irreversible damage occurs. Map 5.3 shows that the *exceedances* of critical loads for sulphur are shown mainly in the Ural Mountains, in boundary regions with the Kazakhstan Steppes, in the Norilsk industrial district at the lower end of the Yenisei River, and in the Far East. The minimal values of critical loads exceedances for sulfates as well as acidity were shown predominantly in the northern part of East Siberia and the Kamchatka Peninsula. In the area between Yenisei and Ob Rivers where industry is concentrated, these exceedances are shown to increase up to 50-100 eq/ha/yr and maximal values (>300 eq/ha/yr) were noted for ecosystems with neutral and alkaline soils. The corresponding exceedances were shown for many regions of the northern part of Asia with maximal values for Ural and Altai Mountains, for boundary regions with Kazahkstan, lower Yenisei river flow, Far East, Sakhalin and South Kurilean islands. The Ural and Altai Mountains, the Far East and the lower Yenisei River flow manifested maximal exceedances of critical load values.

Map 5.2 Distribution of critical loads for sulphur defined for Siberia.

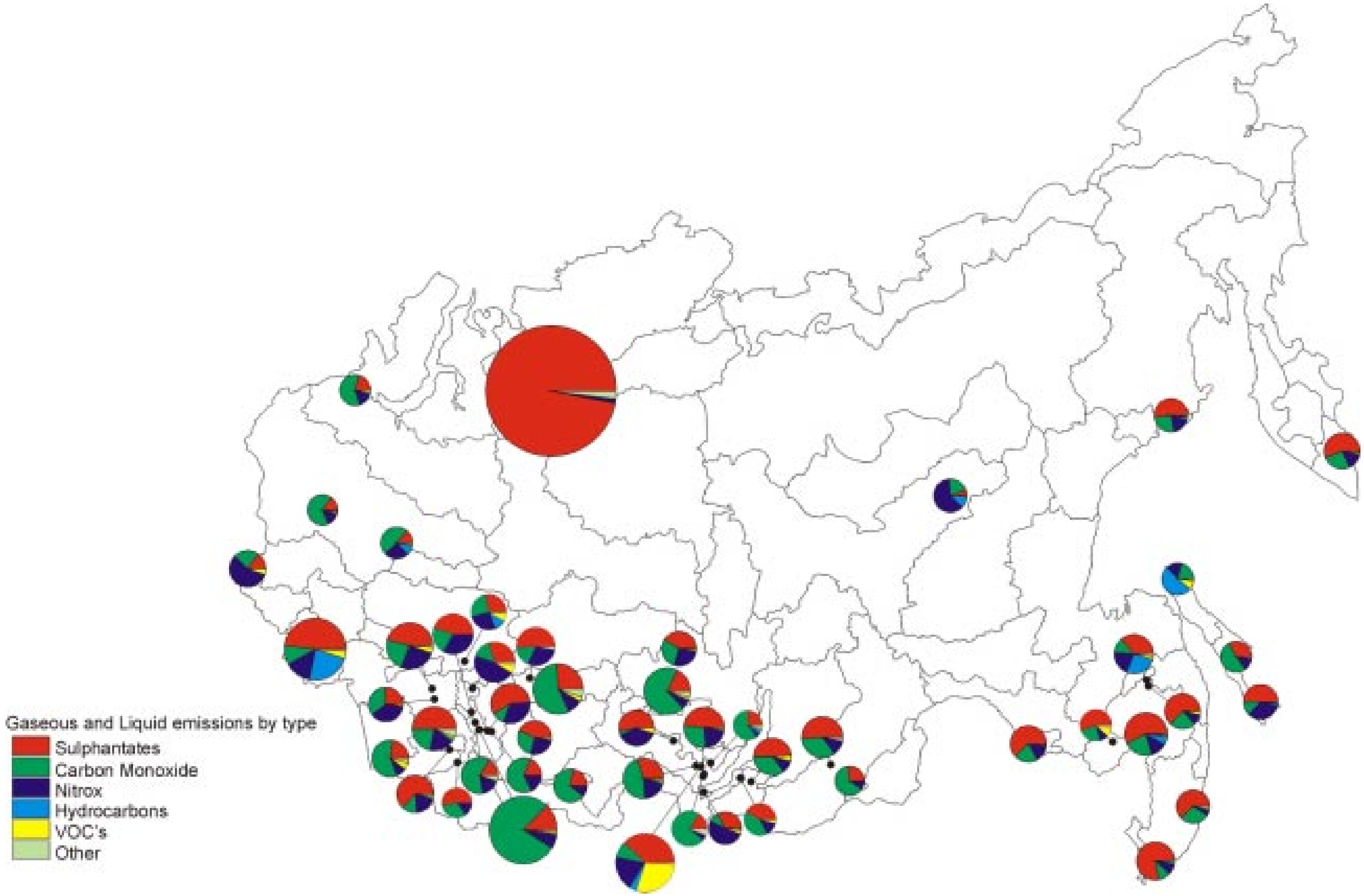


Source for Map 5.2 and 5.3: IIASA, Sustainable Boreal Forest Resources Project.



Map 5.3 Distribution of exceedances of critical loads for sulphur defined for Siberia

Map 5.4 Emissions by volume, location, and type in Siberia. Source: IIASA, Sustainable Boreal Forest Resources Project.



Map 5.4 which shows emissions by total volume as well as by the type of pollution classification corresponds roughly to the results of using critical loads. Areas of exceedances for sulphur (Map 5.3) show up in the following map as total volume of sulphur emitted. While this fact seems obvious, having the idea that much of the sulphur emitted in the region is also deposited there can give policy makers a better idea of what the most cost-effective pollution reduction strategy could be. A sustainable development policy will take a two pronged approach to reduce the levels of emissions in the acutely threatened areas, and focus on prevention of emissions in the more pristine areas. The distribution of pollutants and relative intensities, as well as the carrying capacity and self-cleaning ability of given ecosystems give policy makers a clearer focus on the specific issues of sustainability.

Research on heavy metal and persistent organic pollutants (POPs) critical loads is in the early phases of development. Known particularly for their ability to impede reproduction and nutrient uptake processes, heavy metals and organic pollution also play an important role in the environmental/economic matrix. It is now widely realized that these chemicals have potentially severe impacts upon the environment that must be measured. Bakker and de Vries (1996) describe methodologies for calculating critical loads of these sorts of compounds for soils and surface waters. These developments involve all of the complexities of deciding "what to protect," which environmental criteria are important, and the amount of detail required for modeling. Progress in the near future should be expected in this area.

5.2 Conceptual relation to sustainable development

Differentiation and limits characterize the concept of sustainability. The Brundtland report (WCED, 1987) formulated its perception of unsustainability in terms of a threat to survival: "There are thresholds which cannot be crossed without endangering the basic integrity of the system. Today we are close to many of these thresholds; we must be ever mindful of endangering the survival of life on earth." Thresholds represent values or set of values "above which something is true or will take place and below which it is not or will not" (MCWD, 1994). A threshold in critical loads , for example, is the concentration of a pollutant above which health damages become measurable.

Critical loads gives a natural science definition to sustainability by noting thresholds beyond which irreversible chemical changes will take place. This in itself is neutral, but when coupled with the root concept of sustainable development implies that there is a given point in all types of ecosystems and under all types of anthropogenic pressure after which human environment interactions will have negative long-term consequences. This means that after a certain threshold is crossed for a given region and for a given environment-threatening activity, use of natural resources there will no longer be sustainable and the needs of future generations will be compromised. Developing better analytical tools which assign specific values to bearing capacities of the earth's innumerable different natural functions allows policy makers to see direct relationships between human activity and environmental well-being. Seeing this relationship allows policy makers to assign appropriate regulations without having to narrowly define sustainable development in a broad context.

At this point in the discussion, the conceptual relation of critical loads to sustainable development is clear. This differentiated tool can further the discussion on (international) emissions abatement, based on the root concept of sustainability. In particular, the tool may decrease uncertainty in policy making by defining critical loads for given pollutants and illustrate exceedances. After this point, policy makers can define environmental quality criteria and perform risk assessments based upon these criteria. In years since its introduction, the critical load approach has been broadened to assess different kinds of impacts (other than acidification and eutrophication) (Hettelingh *et al.*, 1995). Consideration, for example, of the direct effects of combinations of chemical air concentrations, heavy metals, and persistent organic compounds (POPs) on flora, fauna, and human health may become important for the scientific support of protocol negotiations for the reduction of pollutants. New calculation methods have moved away from single critical loads towards the future application of multiple critical thresholds. This had led to the creation of protection isolines, which describe combinations of chemical deposition at which protection against environmental degradation with defined endpoints is ensured.[11] These new approaches have made progress in advancing risk assessment for larger issues of sustainability while increasing focus upon specific regional problems.

5.2.1 Thresholds and risk assessment

Finding ecological thresholds is the core of the critical loads concept. After this step, methods of risk assessment can be applied to determine alternatives for "sustainable" environmental policy. Significant progress has been made in setting threshold values for soils in European and some Asian ecosystems. In order to protect forests from the damaging effects of acidification and eutrophication, researchers have set thresholds for pollutant exceedances. Beyond these thresholds, the ecosystem cannot with certainty be protected from irreversible damage (by definition unsustainable). Of relevance for work in Siberia, Sverdrup and Warfvinge (1988) set critical loads to safeguard boreal forest ecosystems by assuming a pH > 4.0-4.3 should be maintained in the O, A and Upper B horizons and a soil solution alkalinity of >0.03 meq 1-1 at the base of the B horizon. For lakes and streams, they found that runoff from the soil should have an alkalinity of at least 0.05 meq 1-1 which equates with pH 6.0. In aquatic systems the water pH affecting fish response is a commonly used variable but base cation concentration and the toxicity of biologically active aluminium species have also been included. These measures contribute to the mapping of ecosystem sensitivity to anthropogenic pollution. Once these sensitivities have been mapped, it is possible to pin-point endangered ecosystems and set target pollution levels to prevent further degradation of forests.

Risk assessment, according to Suter (1993), is "the process of assigning magnitudes and probabilities to the adverse effects of human activities or natural catastrophes." Risk assessment and other methodologies which support the conceptual tools of differentiated analysis of sustainable development involves identifying human-caused environmental hazards, and using measurement to quantify the relationship between the initiating event and the effects. Using critical loads and other differentiated

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[11] For example, a 5-percentile protection isoline reflects the combinations of sulfur and nitrate deposition at which 95 percent of the ecosystems in a grid cell (150km^2) are protected against acidification. When the critical load for nutrient nitrogen is included, the protection isoline for eutrophication is also known. Different isolines correspond to different protection levels, and the 5-percentile protection isoline is used to identify grid cells where more than 5 percent of the ecosystem is at risk.

concepts, policy makers can perform risk assessment to protect the non-human environment and insure that resources available today will last into the future. Risk assessment allows policy makers a way to balance the degree of permissible risk against the cost of risk reduction and against competing risks. Setting target loads for depositions exemplifies this point.

One can observe the way in which a range of target deposition levels affect abatement strategies. For example, targets can be set at higher levels than the critical loads if the political discussion leads to adoption of acceptable preliminary targets as a feasible, first objective. A review of progress might subsequently lead to downward revisions of target values. Targets may also be set below the critical load if evidence indicated that the natural system could recover from anthropogenic damage at a faster rate. By using abatement strategy models it is possible to evaluate cost differences associated with various target values. Ultimately dose-response relationship are required to evaluate damage caused by deposition loads; however, risk assessment offers policy makers a method of “assigning magnitudes and probabilities” to unsustainable human activities.

Critical loads, combined with risk assessment may provide quantitative bases for comparing and prioritizing environmental risks. Because policy making often involves choosing between non-optimal options, characterizing the environmental risks associated with human activities in this way may make choosing a sustainable policy more clear. Critical loads depict locations at which particular stresses on the environment will result in significant damage to ecology and to human health. Combined with this, the risks of various chemical pollutants, e.g. for human health, is known, giving policy makers a tool to help them decide at what levels of risk they are willing to allow human activities to take place.

5.3 Sustainable development in Siberia

After the collapse of the Soviet Union, the world’s attention came to focus more on Siberia for both its environmental assets and for the dynamic human activities there. Policy makers have a key interest in administering the region in such a way that these natural resources can serve as a cornerstone of the Russian economy both in the medium- and long-term.[12] To attain sustainable development in Siberia, several aspects of human-environment interaction have been studied to facilitate “understanding the links to and impacts on sustainable development throughout the boreal zone” (IIASA, 1997). Air pollution, related to acidification and tree die-back, threatens such a development plan. To formulate policy, researchers can use the critical load concept. As an analytical tool for measuring sustainable development, it serves a three-fold function: to indicate present impacts of anthropogenic activities, to indicate the degree of environmental degradation or well-being, and to indicate future risks for deterioration.

In Siberia, impacts of anthropogenic activities became more evident after critical loads analysis was performed. Exceedances of critical loads follow a pattern which correlates with industrial production, the main source of emissions of pollutants. Critical loads presents this first order picture of forest die back due to human activities.

[12] Beginning in 1992, a major study of the Siberian region was launched with IIASA, the Russian Academy of Sciences and The Russian Ministry of Ecology and Natural Resources.

Although relative to other causes of forest die-back, almost all human-caused damage is related to pollution. Not surprisingly, the highest areas of forest die-back (see table 5.3) correlate with Krasnoyarsk Kray, the area where between 1988 and 1993 some 130,000 ha of forests died due to atmospheric emissions. The relative rate of air pollution as a cause for forest loss in Krasnoyarsk Kray was estimated at 40.9 percent. Industrial pollution plays the major role for forest decline: forest losses resulting from air pollution around Norilsk only are of the same order as the territories destroyed by forest fires in the entire kray (Obzor Sanitarnogo Sostoyaniya, 1994).

Table 5.3: Forest Die-back in Siberia caused by Air Pollution, 1989-1993, **ha of dead forests**

Region	*Damaged by human activities*	*of which due to air pollution*	*Relative rate of forest loss due to air pollution, in %*
Altai Kray	0	0	0
Altai Republic	3	3	0.3
Amur oblast	0	0	0
Buriat Republic	239	0	0
Chita oblast	0	0	0
Irkutsk oblast	722	722	0.5
Kamchatskaya oblast	0	0	0
Kemerovo oblast	317	0	0
Khabarovsk Kray	0	0	0
Khakass Republic	0	0	
Khanty-Mansi AO	210	4	0.06
Krasnoyarsk Kray	130203	130203	40.9
Magadan oblast	0	0	0
Novosibirsk oblast	2	2	0.01
Omsk oblast	46	46	0.4
Primorski Kray	0	0	0
Sakhalin oblast	0	0	0
Tomsk oblast	17	17	0.07
Tuva Republic	0	0	0
Tyumen oblast	126	126	0.15
Yakutiya Republic	0	0	0
Yamalo-Nenets AO	0	0	0
Total	131885	131123	na

Source: *Obzor Sanitarnogo Sostoyaniya Lesov Rossii za 1993* god, 1994

In other areas, however, less than one percent of the forest is damaged by anthropogenic emissions, raising the question if the problem is significant at all for the sustainable development discussion. This is an instance in which raw data about atmospheric emissions does not yield enough information for appropriate policy making. After applying critical loads methodology for sulfur and nitrates Nilsson *et al.* (1996) concluded that although emission levels for entire regions were far below critical loads, in the vicinity of the emitters critical loads are substantially exceeded (Nilsson *et al.*, 1996). The most serious exceedances for sulfates and nitrates occurs in the Ural and

Altai mountains, for the boundary regions with Kazakhstan, the Norilsk area, the Far East, Sakhalin, and the southern Kurilean islands (Nilsson *et al.*, 1996).

Second, the critical loads approach indicates the degree of degradation or environmental well-being in Siberia by calculating exceedances of specific pollutants. Map 5.3 above shows the exceedances of critical loads by region of sulfur, again revealing a pattern which correlates with industrial activity. As previously mentioned, studies of acidifying compounds revealed significant insights into the state of the Siberian environment. Russian analyses of so-called self-cleaning ability of air and river dissipation found that most of Siberia has a low capacity for self-cleaning (Nilsson *et al.*, 1996). Siberia-- particularly eastern Siberia—potentially may accumulate pollutants due to the low buffering potential of the ecosystems. Combined with the picture presented above about the levels of emissions and the critical loads which specific ecosystems can bear, policy makers receive the message that although Siberia to date remains largely untouched by anthropogenic pollution, specific subregions manifest acute environmental problems due to human activity. The analysis reveals that pollution remains a problem of regional scale: Most damaged territories include belts surrounding massive industrial zones. At the same time, exceedances of critical loads reveals that the majority of the area is free from pollution damage, as in Yakutiya, the central area of Kraynoyarsk kray, and Magadan oblast.

Kiseleva (1995) noted that the risk for long-distance pollution transportation in the area is minimal. However, although presently it contributes only to the pollution background of Tyumen oblast, there is a potential for this anthropogenic damage. Many of the emissions typical for regional industries are small in particulate size, allowing them to travel thousands of kilometers from their source before deposition.[13] Because of low self-cleaning ability, far-away and still-pristine areas of Siberia have the potential to suffer from long-distance air pollution. Continual comparison of depositions with critical loads values will allow policy makers to monitor the state of the environment in such areas while focusing on restoring as much as possible acutely threatened regions. The analysis for exceedances reveals that the problem of acid rain in Siberia is generally not as acute as in Europe or North America. Generally, sulfur and nitrogen depositions in the region are much lower than in the European part of Russia. However, critical loads values in Siberian ecosystems also tend to be lower, indicating higher sensitivity to stress from pollutants.

Finally, the critical loads concept indicates future risks for deterioration of Siberian ecosystems which lays the basis for prudent decision making for a sustainable development plan. As critical loads and other analytical tools become better defined for the region, policy makers will gain a better idea of the relationship between anthropogenic activities and environmental deterioration. In an ongoing process, it will then be possible to form policies which may allow both for the economic development of natural resources in Siberia without compromising the ability of the natural system to replenish itself or to provide resources into the future. In a region recently entangled in the throes of economic recession and now on the brink of a rush towards development, the critical loads concept provides a way to assess the levels and intensities at which human activities such as forestry, mining, oil extraction, coal and steel production, and transport can occur without causing irreversible damage to the resources upon which the region depends for its life and living.

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[13] These include sulfates, nitrates, ammonium, organic compounds, and heavy metals. The lifetime of these compounds is also somewhat longer, from days to weeks. Koutrakis and Sioutas, 43.

6. Conclusions

In the debate about development and environment, it became evident early on that definitional and measurement problems threatened to shelf the concept of sustainability. However, recent efforts to develop differentiated tools which provide depth and perspective on specific issues have added new vigor to the discussion. Such tools facilitate policy making for sustainable development. Using more specific tools such as critical loads helps clarify both the root concept of sustainable development, as well as clarify the relationship between human activities and the environment in geographically distinct areas. The critical load concept allows policy makers in Siberia to see the thresholds beyond which human activity will destroy resources for the future. In addition, the concept sensitizes policy makers to the limits of specific ecosystems and provides insight into the status of the environment in response to anthropogenic stresses in the region. As work progresses on critical loads calculation, the sub-debate about harmful effects of atmospheric emissions may also move forward. Policy makers could in the future rely more heavily on the concept to guide their choices for abatement strategies. As the tools for measuring sustainable development become more differentiated and more able to provide insight into complex situations, the discussion will move forward with meaning as well as long-term positive results.

The environmental threats posed to Siberian forests from industrial centers are becoming less abstract and more observable using critical loads. Siberian ecosystems have begun to show stress from the accumulation of pollution depositions from industrial cities. While some uncertainty exists as to the log-term effects of air pollution upon its environment, in measurable terms such as species decline or forest die-back, observable impacts indicate that there is cause for concern. Industrial emissions from large production centers regularly emit large masses of toxic chemicals into the air, pollutants which find their way into Siberian soils and water systems. The critical load tool provides a way for analysts to observe environmental impacts in Siberia, and indicates future risks for deterioration of its ecosystems. More dynamic models must come forward to account for accumulation of pollutants, environmental response, and effects upon biodiversity in mountain areas.

An initial attempt to calculate critical loads in the region shows peculiar patterns of exceedances in Siberia's southern-central region (Bashkin *et al*., 1995). While human activities there do not produce high quantities of toxic emissions, surrounding areas (particularly the industrial centers in Kemerovo and Novosibirsk) contribute significant atmospheric pollution. With a generally low self-cleaning capability, Siberian forests absorb and are disproportionately affected by industrial emissions from distant cities. Reducing air pollution in industrial centers in Russia would have a beneficial effect on the air purity and environmental health of Siberian forests.

Using more specific, less dichotomous tools will not reduce the political difficulty of environmental and economic policy making. Critical loads take a snapshot of ecosystem response to atmospheric pollutants. They do not pave the way for a new energy policy in the Russian Federation, nor do they lessen the immediate opportunity costs for reducing industrial emissions. Creating policies which may reduce emissions in the frustrated economic and social climate of Siberia poses a great challenge. Options such as reducing production of inefficient polluting sectors, changing energy policy, or increasing investment in cleaner technology could all place great strains on the fiscal system and could cause unemployment to rise.

Critical load measurements for Siberia have shown where the greatest exceedance lie and may help policy makers create a second best policy for protecting forests and other natural resources. More dynamic models must come forward to account for accumulation of pollutants, environmental response, and effects upon biodiversity. Luxem (1997) notes, "Further work on indicators would focus on the identification and assessment of inter-linkages among the indicators for different levels of sustainable development, the development of highly aggregated indicators and further development of the conceptual framework for indicators of sustainable development." Still in need of extension to pollutants such as heavy metals and organic materials, critical loads methodology has made significant inroads in providing policy makers with a concrete tool to move towards sustainable development in Siberia.

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