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Terrestrial ecosystems, land use and global sustainability

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Abstract: Nearly all of the research on sustainable development to date focuses on the local and regional scales. The objective of this paper is to explore the global-scale aspects of the sustainable development question. By any definition of sustainability, the global life support system must be maintained within a range of variability in which human societies can continue to develop and flourish. The phenomenon of global change strongly suggests that human societies can no longer take for granted that their life support system – the global environment - will continue to operate within those tolerable limits. Global change research is thus becoming a key component in providing the knowledge base needed for societies to tackle the sustainability question at the global scale. The paper presents several examples that show how activities in one region of the earth have direct implications for sustainable development in others.

Resumen: Prácticamente toda la investigación que se realiza actualmente sobre el desarrollo sostenible está enfocada hacia las escalas local y regional. El objetivo de esta contribución es explorar los aspectos de escala global de la cuestión del desarrollo sostenible. De acuerdo a cualquier definición de sostenibilidad, el sistema global de mantenimiento de la vida debe situarse dentro de un intervalo de variación en el que sea posible continuar el desarrollo y florecimiento de las sociedades humanas. El fenómeno del cambio global sugiere fuertemente que las sociedades humanas ya no pueden dar por hecho que sus sistemas de mantenimiento de la vida – el ambiente global – continuará operando dentro de los límites tolerables. Por lo tanto, las investigaciones sobre el cambio global se está convirtiendo en el componente clave que proporciona la base de conocimiento necesaria para que las sociedades aborden la cuestión de la sostenibilidad en una escala global. El artículo presenta varios ejemplos que muestran de qué manera las actividades en una región de la Tierra tienen implicaciones directas para el desarrollo sostenible en otras.

Resumo: Até ao presente, a investigação sobre o desenvolvimento sustentável tem-se confinado à escala local e regional. O objectivo deste trabalho é, assim, o de explorar os aspectos a uma escala global da problemática do desenvolvimento sustentável. Em conformidade com aquela definição de sustentabilidade, o sistema global de suporte de vida deve manter-se dentro do intervalo de variabilidade no qual as sociedades humanas podem continuar a desenvolver-se e a florescer. O fenómeno da mudança global sugere que as sociendades humanas não mais podem ter como garantido que o seu sistema de suporte de vida – o ambiente global – continue a operar dentro de limites toleráveis. A investigação sobre as mudanças globais está assim a tornar-se uma componente chave para proporcionar o conhecimento base necessário para que as sociedades enfrentem as quesotes da sustentabilidade a uma escala global. Este trabalho apresenta vários exemplos que mostram como as actividades numa região da Terra tem implicações directas para o desenvolvimento sustentável noutras regiões.

Key words: Carbon cycle, deforestation, earth system, global change, land degradation, sustainable development.

Introduction

If the 20th century was the century of the atom, characterised by the striking gains in our understanding of particle physics, the 21st century may be the century of the environment, with a concomitant focus on the environmental sciences. Sustainable development has taken centre stage as the paradigm through which environmental research is connected to major issues of societal concern. Although a commonly agreed definition of sustainable development has proven elusive, the concept is well enough understood to provide a useful framework for an accelerating research effort in the environmental sciences, especially in terrestrial ecology and land use.

Nearly all of the sustainability-oriented research to date, however, focuses on local or regional scales. What about the global scale? Can it be assumed that sustainability at the planetary level over long time periods comes automatically if it is achieved at smaller scales? The objective of this paper is to explore the global-scale aspects of the sustainable development question. Although research linking terrestrial ecology to sustainability at the global scale within the framework of the Earth System is in its infancy, some early findings suggest intriguing properties that only emerge at the global scale.

Sustainability at the global scale

By any definition of sustainability, the global life support system must be maintained within a range of variability in which human societies can continue to develop and flourish. The phenomenon of global change strongly suggests that human societies can no longer take for granted that their life support system – the global environment – will continue to operate within those tolerable limits. Global change research is thus becoming a key component in providing the knowledge base needed for societies to tackle the sustainability question at the global scale. The following three examples demonstrate the potential of global change research to contribute to the quest for sustainable development.

Control of glacial-interglacial cycling

Over the past decade there is growing evidence

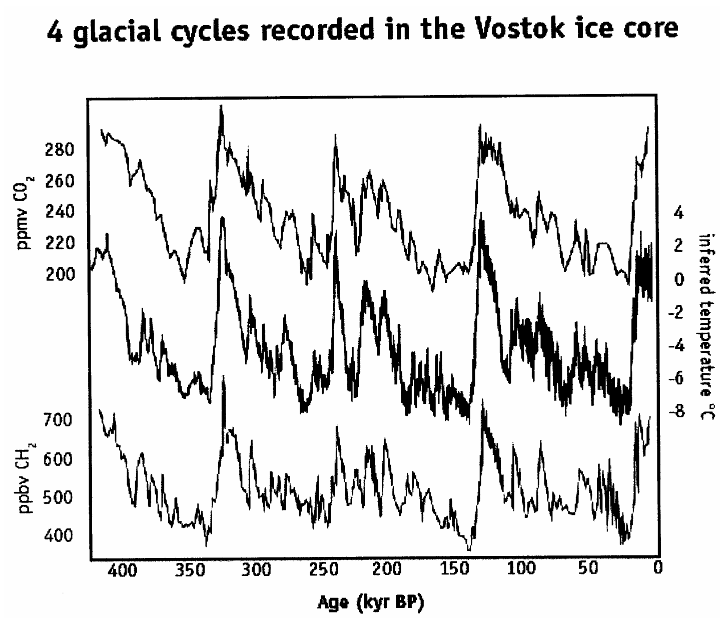

Fig. 1. The 420,000 year Vostok ice core record, showing the regular pattern of atmospheric CO_2 and CH_4 concentrations and inferred temperature through four glacial-interglacial cycles. The upper and lower bounds of all three variables are tightly constrained. These features indicate that Earth's environment operates as a single, self-regulating system. From Petit *et al.* (1999).

that the terrestrial (and the marine) biosphere plays an important role in the functioning of the Earth System. One of the most striking pieces of evidence of the fact that the Earth functions as a single, connected system is the record of variation of atmospheric trace gas concentration and global mean temperature over the last half million years – the now-famous Vostok ice core record (Petit *et al.* 1999, Fig. 1). The record shows a remarkable regularity to both the frequency and amplitude of three key Earth System parameters, atmospheric CO_2 and CH_4 concentrations and mean temperature. In particular, the amplitude of CO_2 concentration is tightly constrained between its glacial value of ca. 180 ppmv and its interglacial value of ca. 280 ppmv.

There are now about a dozen or so hypotheses that attempt to explain the process control that governs the glacial-interglacial cycling (Prentice *et al.* 2001). A recent hypothesis suggests that terrestrial ecology may play a crucial role in setting the upper and lower limits of CO_2 concentration, and thus in controlling the functioning of the Earth System as a whole (Scholes 2002). The hypothesis goes like this. The preferred state of the Earth System is the glacial state in which the CO_2 concentration is approximately 180 ppmv. This level is set by a biospheric compensation point, the point at which terrestrial vegetation can fix just enough carbon to maintain itself but not grow. Dieback is widespread under these conditions and this releases small amounts of CO_2 back to the atmosphere, enough to allow plant growth to be maintained at a low level.

A change in the eccentricity of the Earth's orbit changes the distribution of solar radiation at the Earth's surface. This triggers the release of CO_2 from the ocean to the atmosphere as the surface waters warm and also drives a reorganisation of ocean circulation. A series of large-scale geophysical feed backs continue to push CO_2 from the ocean into the atmosphere. As the atmospheric CO_2 concentration and temperature increase, the terrestrial biosphere grows more vigourously and takes up increasing amounts of CO_2 from the atmosphere. Eventually a new but unstable equilibrium is reached when the rate of CO_2 uptake by terrestrial ecosystem matches the rate of release by the oceans. The equilibrium is unstable because the reinvigorated terrestrial biosphere has also mobilised large amounts of nitrogen, phosphorus and silicon, some of which leaks from the internal terrestrial cycling into river systems and eventually to the ocean. There it stimulates the marine biosphere, which enhances its uptake of CO_2 and subsequent burial of carbon in the deep ocean. This triggers a series of geophysical feedbacks which reverse the CO_2 release and begin the long slide of the Earth System back into the glaciated state.

If this hypothesis is shown to be correct, it has serious implications for sustainable development. First, it raises the obvious question of the current level of atmospheric CO_2, now at ca. 370 ppmv due to anthropogenic emissions. Humanity has now forcefully broken the bounds of glacial-interglacial cycling. What are the long-term implications? Perhaps more importantly, human alteration of terrestrial ecosystems through land-use change, largely the conversion of forests to agriculture, is changing the ability of the terrestrial biosphere to act as a brake on the global cycling of carbon between the ocean, the land and the atmosphere. Thus, human alteration of terrestrial ecosystems may not be only an issue of local or regional sustainability, it may also have serious implications for the sustainability of Earth's life support system as a whole.

Greening of the Sahel

A second example of the role of terrestrial ecosystems in Earth System functioning concerns the pattern of vegetation in North Africa, the waxing and waning of the savanna vegetation in what is now the Sahara Desert. About 6000 years ago virtually the entire desert was covered by savanna similar to the present-day vegetation of the Sahel region. Clearly the climate was different then, and the changes were ultimately driven by small changes in the Earth's orbit. When the changed radiation pattern is used to drive a coupled ocean-atmosphere model, the savanna vegetation in the Sahara region cannot be maintained by the model. The climate dries and the savanna, the initial condition in the model, turns into desert (Claussen & Gayler 1997).

However, when the vegetation itself is fully coupled into the model in an interactive way, the result is different. The feedbacks to the climate via the changed albedo of the Earth's surface as well as evapotranspiration from the savanna vegetation changes the atmospheric circulation patterns in the region sufficiently that enough rainfall is produced to maintain the savanna vegetation. It is also important to note that teleconnections to vegetation in the northern high latitudes, to the boreal forests of Siberia, is also important for the climate system in North Africa. These results are most intriguing. They imply that the interaction of the terrestrial ecosystems in both the North African region and the boreal region far to the north is essential in modulating the behaviour of the climate system such that sufficient rainfall is maintained over the Sahara region.

Even more interesting is the sudden disappearance of the savanna vegetation in the Sahara region about 5,500 years ago (Fig. 2). The changes in the orbital forcing of climate at that time were small and gradual. However, at one point they passed a threshold and the vegetation feedbacks were not sufficient to maintain the favourable climatic regime. The vegetation was quickly lost and the present Sahara Desert was formed. This event shows that the modulating functions of terrestrial vegetation on the Earth System are not without limit, and when the limits are passed, the changes can be sudden and dramatic. Again, this has obvious implications for sustainable development at the regional scale. A knowledge of thresholds is important so that critical changes, with potential severe consequences, can be avoided.

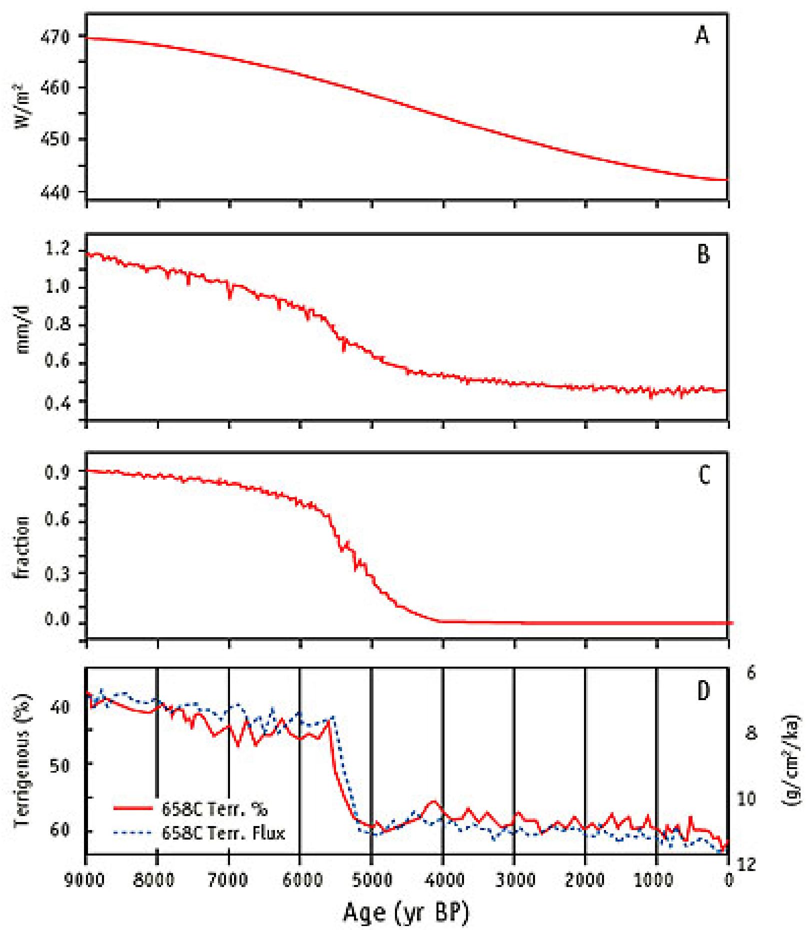

Fig. 2. The browning of the Sahara. (a) Change in amount of solar radiation in the North African region; (b) change in precipitation; (c) change in fraction of vegetation cover; and (d) deposition of sand off the coast of West Africa (solid line – model projections; broken line – observations). From Claussen *et al.* (1999) and de Menocal *et al.* (2000).

Recycling of water by tropical forests

A third example of terrestrial ecosystem control concerns the recycling of water by tropical forests. The forests of the Amazon Basin require large amounts of rainfall to survive, and over 50% of the annual rainfall in the region comes from the recycling of water from the forests themselves, that is, from evapotranspiration from the land surface. Currently deforestation in the region, although an issue of widespread media coverage and global concern, has removed only about 15% of the forests. Thus, the water recycling function of the forests have been largely maintained. However, there are legitimate fears that if a threshold is crossed in the amount of forest converted to grassland or cropping, the water recycling effect of the remaining forest will be insufficient to ensure rainfall at the required levels to maintain the forest. The result could be a sudden conversion of the tropical forests to a savanna or grassland ecosystem.

The results of such a change in vegetation would likely have ramifications far beyond the region itself. Model simulations (R. Avissar, personal communication) suggest that a conversion of the Amazon rainforests into savanna, grassland or cropping systems would affect atmospheric circulation in the entire western hemisphere, with teleconnections around the globe (Fig. 3a & 3b). Thus, even if locally sustainable agricultural systems could be developed and implemented in the Amazon Basin, the impacts could be far-reaching and lead to unsustainability in other parts of the globe.

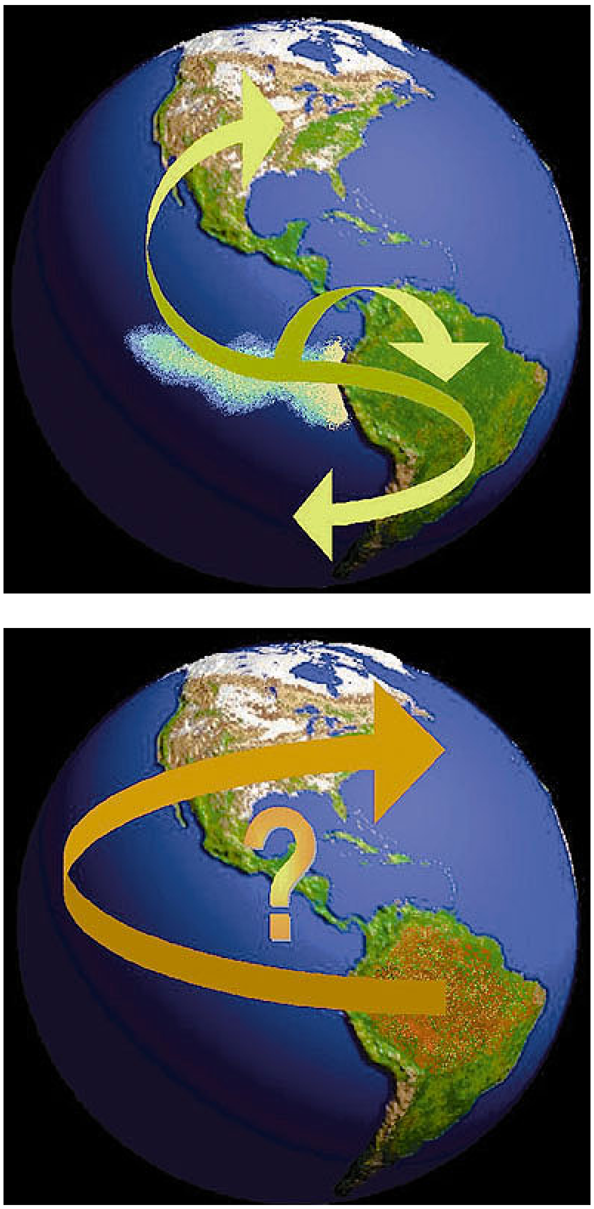

Fig. 3. (a: above, b: below) Projected changes in atmospheric circulation over the western hemisphere if the rainforests of the Amazon Basin are largely or completely converted to agricultural land. (R. Avissar, personal communication).

Regional inequalities

The last example above hints at another feature of the Earth System that is important for sustainable development. In terms of Earth System functioning not all regions are created equal. The Earth's surface is very heterogeneous, and the spatial patterns of oceans and land play a strong role in the functioning of the Earth System. Some regions may play a disproportionately large role in critical Earth System processes, such as the carbon cycle or in influencing atmospheric circulation.

Fig. 4 shows an early attempt at identifying these particularly important regions for the Earth System, the so-called switch-and-choke points (Schellnhuber 2002). It is very interesting to note, in terms of terrestrial ecosystems, that the tropics and the high latitude are both important. Thus, it may be much more important to maintain forests largely intact in Amazonia than in North America. As noted above, converting the Amazon Basin to grassland will likely have global consequences. In contrast, both Europe and the eastern half of North America have been virtually completely de-

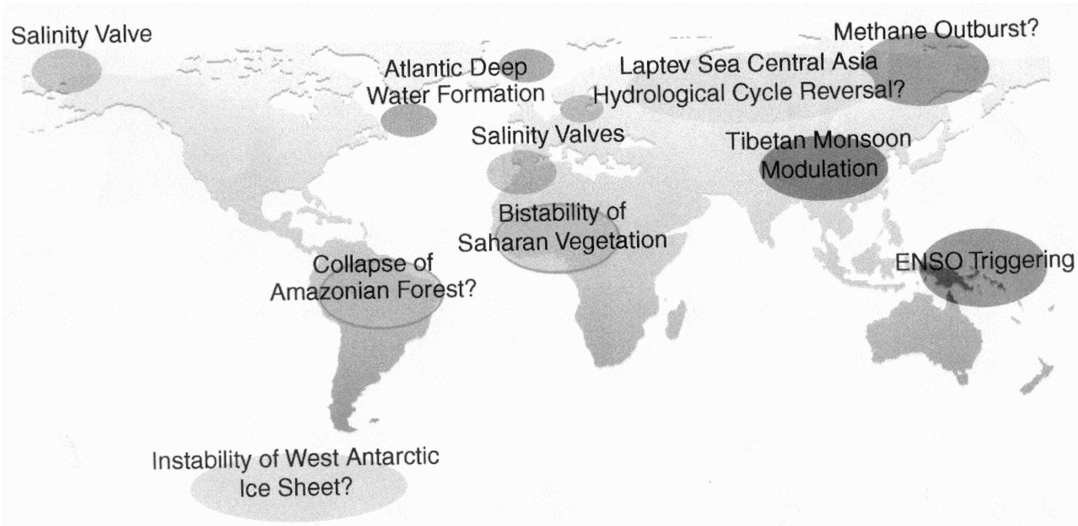

Fig. 4. Potentially important regions for the functioning of the Earth System. From Schellnhuber (2002).

forested with no large effect on the functioning of the Earth System.

What are the implications of this 'lumpiness' of the Earth for sustainable development? It is interesting to conjecture that the developed countries of the world, which lie almost exclusively in the mid-latitudes, have simply been lucky in terms of their position on the planet. They have been able to modify and convert their terrestrial ecosystems with little effect beyond their own localities or regions. The developing regions of the world, largely in the tropics, do not have such a luxury. In addition to the complexities of sustainability issues at local and regional scales, which are considerable, they may well also have to consider the global consequences of their development pathways. Indeed, the international concern over the fate of the Amazonian rainforests are, at least in part, a reflection of this growing realisation. In terms of development, this raises issues of equity, which are a major concern (but beyond the scope of this paper).

Scale issues: Local to regional to global linkages

The connected nature of the Earth System presents significant problems to the sustainability challenge. Connections in both space and time mean that it is often easy to transfer unsustainability to other regions of the world or to the future. Thus, it is most important, in analysing the sustainability of a particular development pathway, to define carefully the system under study and to analyse the transfer of energy and materials into and out of the system. In terms of social and economic aspects of sustainability, the phenomenon of globalisation is a clear case. In some cases developed countries have significantly improved their own local and regional environments by the export of polluting industries to other parts of the planet. Thus, region X in the USA, for example, may appear to be on a much more environmentally sustainable pathway than it was 50 years ago when, in fact, the unsustainable aspects of its development have simply been shifted elsewhere.

In terms of terrestrial ecosystems and land use, two examples illustrate how problems can be advected into or out of systems from areas far removed from the ecosystem under study. In the first case practices in one part of the world, even if they prove to be sustainable, cause problems in locations far removed. The second case is the reverse; attempts to achieve sustainability in one agricultural system are hindered by actions on other continents.

In many parts of Southeast Asia forests have been converted into agricultural systems. A common practice in many regions is to burn the slash at the end of the growing season, after the harvest, both to remove the excess biomass and to release the nutrients stored in the biomass so that they can be returned to the soil in preparation for the next season's crop. Whether or not this practice is ecologically sustainable in the long term for the particular locations in which it is practised, it is almost certainly not sustainable from a global perspective.

Satellite images show the production and transport of carbon monoxide from its source, the agricultural fires primarily in Thailand, all the way across the Pacific Ocean to the west coast of North America. Carbon monoxide is formed by the incomplete combustion of biomass. It is a chemical precursor to the formation of ozone, one of the ingredients of photochemical smog. Thus, localities which may have taken steps to improve their own air quality may find that agricultural practises on the other side of the world will affect ability to achieve targets.

The second example focuses on the well-known case of the Sahel region of North Africa, where there have been concerns of severe land degradation, desertification and possibly mass starvation. During the 1970s and 1980s at least, the conventional wisdom was that the population of the region was too high and the agricultural practices were not appropriate to the ecosystems of the Sahel. The case was often highlighted as one in which there is clearly unsustainable development. However, recent evidence shows that the situation is much more complex. It is even possible that the apparent unsustainable nature of the development pathways in recent decades is not due to local conditions at all, but rather has been imposed on the people and ecosystems of the region by practises much further away.

The effect is related to the burning of fossil fuels in Europe and North America. Fossil fuel combustion influences the Earth System in a number of ways, including the production of sulphate aerosols. Since about 1990, the production of sulphate aerosols has been significantly reduced in many parts of North America and Europe, but in the decades before that time, sulphate aerosols were an important local and regional air quality issue. In addition to their local and regional effects on air quality, sulphate aerosols change the radiative of the atmosphere in a direction opposite to that of greenhouse gases, i.e., they lead to cooling. The effect is not global, however. The aerosols have a short lifetime in the atmosphere and are rained out on to the land or sea surface before they have circulated widely around the atmosphere. Thus, the cooling is a regional effect.

The cooling over Europe and North America in the 1960s, 70s and 80s changed the temperature gradient in the atmosphere between the North Atlantic region and the tropics and subtropics further south. This in turn changed the atmospheric circulation patterns and triggered to a change in the positioning of the African monsoon system. The result was a shift in the rainfall patterns over the North African region, and a significantly drier climate in the Sahel during those decades. Land degradation increased during that time and there were dire predictions of the Sahara Desert marching southwards. The resulting impacts on the people in the region were severe, with an increase in poverty, malnutrition and starvation. This increase in land degradation in the region has often been cited as a case of grazing and cropping pressure, driven by population increase, overwhelming the resilience of the natural ecosystem, whereas in reality the problem may have been caused in large part by forcings far away from North Africa.

What evidence is there that this assertion is actually true? The change in global precipitation patterns simulated when a climate model is forced by changes in the observed sulphate aerosol loadings in the northern hemisphere agrees well with the observed precipitation changes around the world during the last century. The agreement for the North African region is remarkably good. Further evidence comes from the changes in the 1990s. Sulphate aerosol loadings were significantly decreased during that decade in Europe and North America in response to pressure from their own population to improve air quality. The climate model, driven by reduced sulphate loading, simulates a return of the African monsoon to its earlier pattern, bringing increased rainfall to the Sahel. This is precisely what was observed in the 1990s, leading to an easing of the degradation problem and an increase in productivity of the ecosystems of the region. It is significant to note that the grazing and cropping patterns of the people in the region did not change significantly during this transition to lesser land degradation.

Although there is no conclusive proof of the reality of the linkages described above, the circumstantial evidence is strong. Given the connectivity of forcings and feedbacks in the functioning of the Earth System, it should not be surprising that forcings of sufficient magnitude will reverberate through the Earth System in ways that are often counter intuitive and difficult to predict.

The implications for sustainable development are strikingly clear in this last example. In very few cases localities or regions can be considered in isolation. We are all downwind from somebody else and all but a very few of us are also downstream from somebody else. We are increasingly connected culturally, socially and economically through globalisation, leading to some benefits but also homogenising cultures and accentuating inequalities. We are also intimately part of one connected, integrated biophysical life support system. Activities in one part of the world are increasingly affecting quality of life in others. Sustainable development is thus a global-scale concern. Our growing understanding of the dynamics of the terrestrial human-environment system must be integrated with the emerging field of Earth System science to provide the overall knowledge base required to support sustainable development.

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