Global trade, food production and ecosystem support: Making the interactions visible

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Doctoral Thesis in Natural Resource Management

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I would like to dedicate this to Eunie
– thanks for my roots.
You taught me the love and art of gardening.
Sure do miss sittin’ on the porch with you.
We did not inherit the land from our forefathers. We are borrowing it from our children.

- Amish belief
Abstract

Modern food production is a complex, globalized system in which what we eat and how it is produced are increasingly disconnected. This thesis examines some of the ways in which global trade has changed the mix of inputs to food and feed, and how this affects food security and our perceptions of sustainability. One useful indicator of the ecological impact of trade in food and feed products is the Appropriated Ecosystem Areas (ArEAs), which estimates the terrestrial and aquatic areas needed to produce all the inputs to particular products.

The method is introduced in Paper I and used to calculate and track changes in imported subsidies to Swedish agriculture over the period 1962-1994. In 1994, Swedish consumers needed agricultural areas outside their national borders to satisfy more than a third of their food consumption needs. The method is then applied to Swedish meat production in Paper II to show that the term “Made in Sweden” is often a misnomer. In 1999, almost 80% of manufactured feed for Swedish pigs, cattle and chickens was dependent on imported inputs, mainly from Europe, Southeast Asia and South America. Paper III examines ecosystem subsidies to intensive aquaculture in two nations: shrimp production in Thailand and salmon production in Norway. In both countries, aquaculture was shown to rely increasingly on imported subsidies. The rapid expansion of aquaculture turned these countries from fishmeal net exporters to fishmeal net importers, increasingly using inputs from the Southeastern Pacific Ocean.

As the examined agricultural and aquacultural production systems became globalized, levels of dependence on other nations’ ecosystems, the number of external supply sources, and the distance to these sources steadily increased. Dependence on other nations is not problematic, as long as we are able to acknowledge these links and sustainably manage resources both at home and abroad. However, ecosystem subsidies are seldom recognized or made explicit in national policy or economic accounts. Economic systems are generally not designed to receive feedbacks when the status of remote ecosystems changes, much less to respond in an ecologically sensitive manner. Papers IV and V discuss the problem of “masking” of the true environmental costs of production for trade. One of our conclusions is that, while the ArEAs approach is a useful tool for illuminating environmentally-based subsidies in the policy arena, it does not reflect all of the costs. Current agricultural and aquacultural production methods have generated substantial increases in production levels, but if policy continues to support the focus on yield and production increases alone, taking the work of ecosystems for granted, vulnerability can result. Thus, a challenge is to develop a set of complementary tools that can be used in economic accounting at national and international scales that address ecosystem support and performance.

We conclude that future resilience in food production systems will require more explicit links between consumers and the work of supporting ecosystems, locally and in other regions of the world, and that food security planning will require active management of the capacity of all involved ecosystems to sustain food production.
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This thesis is based on the following papers that are referred to in this summary chapter by their roman numerals. All papers are reprinted with the kind permission of the copyright holders.


II. Deutsch, L, and Björklund, J. Made in Sweden? Re-defining the Swedish animal production system. Submitted manuscript.


**Introduction**

Ecological systems provide the biophysical foundation for societal development. They generate the natural resources and ecosystem services supporting human production and consumption. In most of the world, natural resource problems are growing. Two billion people depend on the ecosystem services of highly vulnerable drylands, many marine fisheries have collapsed and others are fully exploited and vulnerable, and changes in biogeochemical cycles threaten water supplies and coastal seas in many regions (World Bank 2003). There are many other examples. Natural resource problems are connected, regionally and globally, through markets, transboundary pollutants, demands for water flows, changes in geographic distributions of organisms including pathogens and invading species, and through national and multinational policies. Any action to address them must consider complex tradeoffs.

Because we are dependent on ecosystems for our basic food security we must assure their continued functioning. Although food production gives rise to just a portion of the human activities affecting the world’s ecosystems today, food production methods play a definitive role in the alteration of ecosystems and their capacity to generate ecosystem services (Björklund et al. 1999, Moberg and Rönback 2003). The Green Revolution initiated the industrialization of agricultural production world wide and food production volumes have increased dramatically since the 1960s. For example, the volume of cereals has more than doubled (Rosegrant et al. 2001) and world meat production has more than tripled (FAOSTAT 2003). The more recent Blue Revolution in aquaculture (not including aquatic plants) has seen more then seven-fold increases in volumes in just the last 20 years (FIGIS 2004, FishStat Plus 2004).

Further, since the 1960s, the economic value of food products traded worldwide has increased more than ten-fold (FAO 2000a) to equal USD 442 billion by 2000 (World Trade Organization 2003). Although global agricultural trade is relatively limited in comparison to total production, it is nevertheless large. For example, although only 17 % of all wheat production, the largest
export cereal crop, is traded, the absolute size of this trade is equal to the entire EU domestic wheat market in value (World Trade Organization 2003). Thus, many are dependent on trade for food and livelihoods.

The expansion of the global food market has resulted in a reshuffling of resources over the entire globe, providing food and livelihood possibilities where they may have been previously limited, unavailable or untenable (e.g. food provision to cities, or the development of aquaculture production through imports of feed inputs). This market expansion has also been accompanied by significant changes in ecosystem areas, such as the transformations of the Brazilian cerrado to soybean fields (Fearnside 2001) and of Thai mangroves to shrimp farms (Flaherty and Karnjanakesorn 1995).

Environmental impacts related to agriculture are well known. While low-input production is not always better, and not all intensification is bad (e.g., conservation tillage), intensified crop production has well-known environmental impacts that include alterations of biogeochemical flows, use of pesticides, soil erosion, salinization, groundwater problems, and loss of biodiversity (Bennett 2000, Environment and Development Economics 2001, Matson et al. 1997, Tilman 1999, World Resources Institute 2000). Ecosystem degradation related to agriculture is expected to continue in the near future, but the FAO asserts that it will do so at a slower rate than in the past (FAO 2003b).

Within the marine realm, the industrialization of fisheries and aquaculture production has put similar pressures on coastal ecosystems (Jackson et al. 2001, Pauly et al. 2002). Today, almost three-quarters of the world’s fisheries are fished at their biological limits or overfished (Botsford et al. 1997, Burke et al. 2000, Garcia and de Leiva Moreno 2000, Pauly et al. 2002). As stocks of major predatory fishes decline (Hutchings 2000, Jackson et al. 2001, Worm et al. 2003) we are “fishing further down the food web” (Pauly et al. 1998) and “farming up the food web” for making intensive aquaculture production possible (Naylor et al. 2000). Meanwhile, intensive aquaculture production has been criticized for several major, negative environmental effects. These include the net loss of fish protein in the production of carnivorous species such as salmon and shrimp (Naylor et al. 2000); deforestation of mangroves and loss of accompanying ecosystem services (e.g., habitat, storm protection, prevention of coastline erosion) (Moberg and Rönnback 2003); pollution of surrounding waters with pesticides, antibiotics and nutrients (Folke and Kautsky 1989, Gräslund 2004). In other words, there are similarities in both terrestrial and aquatic food production systems and markets and trade connects them regionally and globally.
**Vulnerability, food production and trade**

Trade enables the usage of ecosystem areas not otherwise available. Hence, trade removes the importing nation’s limits on production and consumption (as long as it can pay for the goods), but the ecological limitations – and, potentially, ecological damage – still remain in the ecosystems of the exporting regions (Papers I-III). In the case where trade is pursued due to local limitations, trade has allowed us to expand our appropriation, only moved the necessary ecological support to other nations, it has not removed the net ecosystem support needed for expanded consumption. In this sense, the global trade system plays a role in ecosystem dynamics and is even a major driving force that affects the capabilities of many ecosystems to provide natural resources, ecosystem services and support (Papers II and III).

It seems that we have currently increased demands on the planet to the point where ecosystems at are affected a global scale (Steffen et al. 2004, Western 2001, Vitousek et al. 1997). It has been proposed that humans are the largest evolutionary force currently (Palumbi 2001), and demand so much from terrestrial ecosystems that trade offs between agricultural productivity and economic externalities (such as loss of biodiversity or nutrient leakages) are no longer exceptions, but the rule (Ashby 2003). A similar situation may be developing in the oceans through aquaculture (Paper III). The scale of present ecosystem changes, as well as potentially synergistic effects of such changes (Paine 1998), sparked my concern for increased vulnerability in ecosystem capacity and, thus, for the long-term capabilities of ecosystems to support food production for humans.

Farming systems, whether of crops, animal husbandry or fish, are by definition integrated social-ecological systems (Berkes and Folke 1998). These altered ecosystems are not a new phenomenon; humans have been affecting ecosystems for millennia (Diamond 1997, Jackson et al. 2001, Redman 1999, van der Leeuw 2000) but are doing so now at a faster pace and at a global scale (Steffen et al. 2004). Questions of whether, for example, fisheries, pollution, or climate change are leaving a lasting mark on marine systems do not have clear cause-and-effect answers. Instead, the combined and often synergistic human pressures, such as emissions of waste and pollutants, removal of biological organization (e.g. trophic levels, key species), changes in magnitude, frequency and duration of disturbances including climate change, seem to make ecosystems
more vulnerable to changes that previously could be absorbed (Folke et al. 2004). As a consequence, ecosystems may suddenly shift from humanly desirable to less desirable states, i.e., lose their capacity to generate ecosystem services (Scheffer et al. 2001). Such loss of resilience may lead to severe social and economic consequences (Folke et al. 2002a).

I feel there is a sense of urgency that ecosystems need to be managed sustainably. The scale of the human endeavour has expanded to the point where ecosystems are so adversely affected, that thresholds of ecosystem resilience may be breached in more than one place at a time (Folke et al. 2004). Sustainable management does not mean eliminating human resource use or impacts on ecosystems (Zabel et al. 2003). It implies using without abusing (Pritchard et al. 2000). It encourages us to realize that we are an integral part of the biosphere and actively manage as such (Folke 1998). This means that it is in the self-interest of consumers to ensure the maintenance of the support capacity of ecosystems that they depend upon, irrespective of country of origin. Thus, dependence is not a problem, as long as we are able to manage ecosystems both at home and abroad.

However, the global food system is getting larger and more difficult to manage. If one cannot see the entire system and/or receive feedback as to performance due to distances, increased number of partners and time lags, there is a risk of fragmented, untimely and improper decisions and actions. As a consequence, unsustainable practices may then be accelerated and bring us closer to undesirable ecological thresholds and increasing vulnerability.

Hence, I do not propose that trade in itself is an objectionable human activity. It is the direction, content and context, and associated value systems and institutional frameworks of trade that will influence its impact on the environment. Since humans must use natural resources to survive, and trade is an effective mechanism to distribute goods and services around the globe (Costanza et al. 1995), we must be clear about the degree of societal dependence that exists today with respect to the use of ecosystem support and services (Andersson et al. 1995, Daily 1997, Pauly and Christensen 1995, Vitousek et al. 1986, Vitousek et al. 1997). It is this dependence that is the focus of the thesis: ‘Global trade, food production and ecosystem support: Making the interactions visible’.
Objectives of the thesis

The overall objective of my thesis is to illuminate the interactions between ecosystem support and food production systems enabled by global trade, both spatially and temporally, and relate these interactions to present indicators and policies - with the ultimate goal of increasing understanding and enabling better decision making.

In Papers I-III ecosystem support is quantified. The last two papers (IV and V) of the thesis discuss and critique the indicators used measure this support and indicators of ecosystem performance in general. Papers I-II measure the ecosystem support areas necessary to support Swedish food consumption and agricultural production and how they have changed since the 1960s. Paper III examines the marine support areas necessary for the growth of shrimp aquaculture in Thailand and the salmon industry in Norway since the mid-1980s.

Ecosystem support is analyzed in several complementary ways in Papers I-III. First, the amount of direct ecosystem support is quantified. For the Swedish studies, support is estimated by computing the agricultural and marine areas necessary to produce food goods. For the Norwegian and Thai cases, the trade flow volumes are compared. Second, changes over time in the size and composition of ecosystem support are discussed. Third, imports are differentiated from consumption to quantify levels of external ecosystem dependence, relate them to the actual local ecosystems providing the resources, and analyze the evolution and structure of the production system. Fourth, there is an assessment of current measures of this dependence and of the environmental effects of intensification of production practices. We are particularly interested in indicators that internalize, and hence make explicit imported production as a part of domestic production (a truer accounting of resource use) and those that reflect ecosystem performance. Lastly, in all the cases there is an additional discussion of some of the major driving forces behind changes in production.

As noted above, increasing import dependence is not problematic if we are managing imported ecosystem capacity sustainably. Papers IV and V discuss whether present indicators reflect this capacity, including a critique of areal indicators (Paper IV) and an in-depth summary of existing Swedish environmental indicators (Paper V).
Methods

In order to evaluate human dependence on ecological life-support systems I use a combination of indicators (Hammer 1991). In Papers I and II I estimate the appropriated ecosystem areas (ArEAs) used to satisfy consumption demands. ArEAs in my studies measure the arable land areas upon which crop production and grazing take place, and the marine areas necessary to produce the fish meal used in animal feed. (Details on how to calculate ArEAs and sources of data can be found in Paper I.) Paper III compiles available trade data to quantify trade flows in tonnes (MT) and map out supply sources for the single resource fishmeal.

Papers IV and V address the extent to which present indicators capture the dynamic processes of ecosystem change, the capacity of ecosystems to sustain the flow of ecosystem services and promotes the development of environmental indicators that focus on the ecosystem performance and resilience. In this thesis, I use the concept of resilience – the capacity to absorb and respond to disturbance and reorganize following disturbance, without moving into less desirable states (Gunderson and Holling 2002, Holling 1973) - as a way to organize thoughts around ecosystem performance (Carpenter et al. 2001, Folke et al. 2002b).

**Swedish food consumption and meat production - Papers I and II**

In Paper I, Swedish food consumption from 1962 to 1994 is examined to estimate the ecosystem support needed to sustain it. The study has five main foci (Table 1, Paper I). First, we estimate total land-based agricultural consumption. Second, changes over time in the size and composition of these land areas are discussed. Third, some of the essentially “hidden” ecosystem support areas subsidizing animal products’ production from both within and outside Sweden are differentiated. Here we quantify the animal feed ArEAs, including the marine ArEAs necessary for fishmeal production. Fourth, we discuss the level of Swedish society’s interdependence in the global agricultural market, as well as whom Sweden is dependent upon. Finally, the consequences of intensification of agriculture production methods are discussed in relation to areal ArEA measurements and ecosystem performance.
Figure 1. Appropriated ecosystem areas for Swedish food consumption – ha/person 1962 and 1994. Total consumption is the combination of the four basic components: domestic crop production, on-farm feed production, fodder areas and imports, i.e., excluding exports. Proportional consumption is the relative importance of one component of consumption to total consumption. This figure includes net imports of primary equivalents of meat, milk and egg products, and live animals. Marine ArEAs are not included in these estimates. From Paper I.

Through international trade and intensification of agricultural production Swedish citizens were able to reduce the total ecosystem areas appropriated for food consumption by almost one-third since the 1960s (Fig. 1 - note that the marine ArEAs are not included in this figure). Swedish inhabitants are highly dependent on agricultural areas outside their borders for more than one-third of their food consumption and the majority of imports are for animal products’ consumption (i.e., meat, milk and egg products) (Paper I). Since the support necessary for animal products’ consumption was so dominant and the level of dependence on agricultural areas is even less apparent for indirect consumption, i.e., those areas needed indirectly to support production as animal feed, we decided to examine the development of Swedish animal production more closely (Paper II).

In this second study, we analyzed what ‘domestically produced’ means in relation to the Swedish animal production system. To do this, we first
determined the level of dependency of the Swedish animal production system on ecosystems inside and outside Sweden for the year 1999, and how this has changed since the 1960s. Arguing that animal production should be closely tied to the origin of animals’ feed, we chose to focus on animal feed as our link between production and ecosystem support. We quantified the agricultural areas necessary to provide the feed consumed by pigs, cattle, and chickens raised in Sweden, i.e., the total areas of arable farm land necessary to produce feed crops on-farm (including roughage for hay silage and pasture areas), with particular attention on the inputs necessary for manufactured feeds in Sweden and abroad. We also estimated the ecological support provided by marine areas for the fishmeal used as an input in manufactured feeds. This study also addressed the ecological consequences of the changes in the animal production system in Sweden and abroad, as well as implications for food safety in Sweden.

The net result of consumption and production changes was that local farm areas used for animal production have decreased 30% since 1962. A major reason for this is the proportion of areas used for manufactured feed production, as a fraction of total animal feed support, increased from one-fourth to one-third between 1962 and 1999. Sweden is highly dependent on foreign ecosystem support for this type of feed production. In 1999, almost 80% of the agricultural areas needed to produce feed inputs for manufactured feed were located outside of Sweden. In fact, today, Sweden would need to increase total animal feed support areas by approximately 25% above present acreage to be self-sufficient in feed. Thus, there are large subsidies provided by other nations and remote ecosystems that support Swedish meat production. However, present measures do not recognize the entirety of the modern animal production system, nor its dependence on foreign ecosystem support via imports. We propose new measures to expand production system boundaries and increase transparency.

We realize that ArEA measures reveal neither the ecological consequences of agricultural intensification, nor the capacity of ecosystems to sustain consumption. We conclude that areal analyses must be combined with other studies to indicate effects of intensification on ecosystem performance. We, therefore, include an in-depth discussion of these effects in both papers. We provide a historical summary of the intensification of Sweden’s own agricultural systems (Table 3, Paper I). In Paper II, we discuss the ecological consequences of consumption changes and the change in feed production strategy in Sweden since the 1960s, including the loss of recirculation of nutrients, landscape changes, biodiversity loss and the accumulation of heavy metals in Swedish soils.
We also discuss specific environmental effects of production abroad for the two largest feed inputs: soybeans from Brazil and palm kernels from Malaysia.

The method is insufficient to determine if present consumers and future generations have increased their food security as they have reduced their use of agricultural ecosystem areas. However, ArEAs have proven to be an effective tool to discern the level of food consumption dependent on ecosystems beyond national borders. The intent of this study was to widen discussion of agricultural production in Sweden to include production systems in other countries. We can conclude that Swedish citizens are highly dependent on the capacity of other nations’ ecosystems to generate resources and services, and should be aware of this when making consumption and policy choices.

**Feeding aquaculture growth through globalization – Paper III**

We study similarly intensive animal production systems in Paper III, the modern, intensive shrimp and salmon aquaculture industries. As in Paper II, we concentrate our analysis on feed inputs, but here we limit our focus to one key protein source, fishmeal. We discuss the production chain of the aquaculture industry in the global food system and analyze the structure and trade flows. We have not attempted to analyze remaining portions of the chain, e.g., distribution and consumption, in detail. We discern the sources of the fishmeal for the two case studies of Thailand and Norway by mapping out the trade flows of this feed input between 1980 and 2000. This is the period of major expansion in commercial shrimp and salmon aquaculture industry that is dominated by these two countries, respectively. We discuss the expansion of the size, number and location of marine support areas. Through our analysis, we illuminate some of the challenges facing aquaculture.

Like the industrialized animal production systems of Sweden (Paper II), aquaculture has grown into a highly globalized industry. In Paper III, we identify a pattern of increasing import dependence as the national aquaculture industries develop. Over the period studied, both nations expanded their level of imports and dependence on marine ecosystem support of other nations from an initial level of domestic self-sufficiency. Fig. 2 of this summary exemplifies our findings in Paper III. Using Thailand as an example, we analyze fishmeal import data for several periods. The year 1988 represents the initial stage of the industry with little fishmeal trade. By 1990, the aquaculture industry had begun to take off
and Thailand became a net importer of fishmeal. Trade data for 1995, are representative of when the aquaculture industry and fishmeal imports reach their height. The line graph shows import, export and consumption levels of fishmeal throughout the entire period of 1980-2000. For the complete figures for both Thailand and Norway please see Paper III, Figs. 3 and 4.

![Figure 2](image1)

**Figure 2.** Imported fishmeal to Thailand 1988, 1990, and 1995, and fishmeal consumption and trade amounts 1980-2000. The amount of fishmeal is in metric tonnes and numbers in parentheses are percentage of total imports. Adapted from Paper III.

Even nations that have well-developed fisheries sectors and have, historically, been net exporters of fishmeal may eventually need to import if demand is great enough. This was clearly the case for fishmeal trade as the intensive aquaculture industries developed in Thailand and Norway. We also see that both nations increased the overall number of import sources of fishmeal (trade partners) to a maximum in the mid-90s, but reduced this number somewhat by 2000. By 2000, both nations had only 3 – 4 key source nations that provide at least 90% of all imports. Further, both nations expanded the geographic reach of fishmeal
provision with the same 3 sources (Denmark, Chile and Peru) complemented by a regional supplier each (Thailand uses the Rep of Korea and Norway uses Iceland). Thus, very broadly, in 2000 both had two geographically alternate sources of supply: 1) the combination of Chile and Peru in South America, and 2) a regional complement, i.e., Thailand imported from Japan and the Republic of Korea and Norway imported from Iceland and Denmark.

Previous research has not focused on the size and location of remote marine ecosystem support. This study illuminates the expansion of the industry enabled by increased import support and links this support to increasingly distant sources. The global scope of our findings is then discussed in the context of sustainable seafood production. Aquaculture has been proposed to contribute to future protein needs and solving the global fisheries crisis by reducing fishing pressure (FAO 2003a). We challenge whether the development of intensive aquaculture will increase seafood production by attempting to substitute aquaculture farming for sustainable fisheries practices. Fishmeal trade could be interpreted as an example of how the global market can enable nations to increase production beyond national limitations by importing. However, we question whether this production is in fact increasing overall demands for fish protein and whether the increased production is facilitated by global fishmeal trade. Market incentives to produce cash crop species such as shrimp and salmon are strong, but the present global aquaculture industry lacks incentives to account for ecosystem support and capacity. Thus, it is currently difficult to see how the growing aquaculture industry will be able to provide the sorely needed reduction of fishing pressure.

**Indicators of ecosystem performance – Papers IV and V**

To bring scientific evaluation into the policy arena and raise consumer awareness of ecosystem support, we need ecologically-grounded tools with communicative power. **Paper IV** discusses the calculation methods and applications of areal indicators such as the ArEAs. Like all indicators the ArEA has its limitations. **Paper I** showed that Sweden has decreased the size of the agricultural areas it uses by one-third since 1962 through international trade and intensification of agricultural production. However, these changes in areas did not reflect the ecological consequences of agricultural intensification. Further, ArEAs are static measures, contrasting with the view of ecosystems as complex adaptive systems
with non-linearities, discontinuities, multiple-stability domains and thresholds (Carpenter and Cottingham 1997, Holling et al. 1996, Levin 1998). They do not provide information on the resilience of the system, or how close to thresholds the support capacity might be (Limburg et al. 2002, Scheffer et al. 2001).

However, we use and will continue to use this measurement because gives a clearly comprehensible indication of the dependence of humans on large ecosystem areas for their welfare and survival. This is particularly relevant today, when people are removing themselves both physically and mentally from contact with ecosystems (Hansson and Wackernagel 1999) through urbanization at a scale unheard of in the past, but nevertheless continue to make consumption choices that impact on these systems. We use this measure to address the pre-analytic vision - the level of understanding that exists before policy objectives are defined (Daly and Cobb 1989) – in our attempt to foster a worldview of humans as a part of nature.

**Resilience and multiple states**

1. Coral dominance, clear water, grassland
2. Overfishing, coastal eutrophication, phosphorous accumulation in soil and mud, fire prevention
3. Disease, bleaching, hurricane, flooding, warming, overexploitation of predators, heavy rainfall and intense grazing
4. Algal dominance, turbid water, shrub-bushland

Figure 3. Complex ecosystems tend to have more than one state and can slide between states (Scheffer et al., 2001). For example, in 1) the reef is in a state of coral dominance. In 2) the reef is still dominated by corals, but ecosystem resilience is eroding as a consequence of human activities (e.g. fisheries exploitation reduces diversity within the functional group of grazers and eutrophication from human activities on land increases algal growth). Consequently, 3) the system is progressively becoming more vulnerable to disturbances that previously could be absorbed (e.g. hurricanes and diseases). Such
events might now push the reef into an undesirable state of algal dominance 4) and cause loss of essential ecosystem services. Adapted from Paper V.

However, we cannot ignore the negative consequences of some production methods. Additional indicators are needed to comment on the effects of intensification on ecosystem performance and, thus, resilience in Swedish agricultural ecosystems. In Paper V, we examine how Swedish national policy addresses ecosystem performance by doing an inventory and an analysis of the indicators used by five of the most influential governmental agencies and the amount of protected areas established in Sweden.

Most of the indicators in Swedish policy tend to address energy and material flows. A few indicators address the processes of ecosystem performance through examination of the state of ecosystems or parts of them. Although most of the existing Swedish sustainability indicators concentrate on the current state of the system or service, some indicators strive to improve the capacity of ecological systems to provide ecosystem services. Although Swedish policy deserves praise for the relative quality of indicators in comparison to fellow EU members, indicators that better reflect the dynamic capacity of ecosystems are sorely needed. Thus, we encourage the development of indicators of resilience. These differ from indicators reflecting the current state of the system or flows of ecosystem services (Carpenter et al. 2001). Resilience indicators focus on the underlying processes and variables that generate and sustain the flows of services, the ecosystem capacity. We discuss the need to understand complex ecosystems to avoid an erosion of resilience which could cause a shift from one ecosystem state to another (fig 3.). These states are less desirable due to reduced or increasingly unpredictable provision of ecosystem services or increased unpredictability.

Discussion

A major challenge for nations today is to develop and maintain resilient food production systems. Important qualities of resilient food systems are that they cause and enable stakeholders to recognize and maintain their links to ecosystem support, locally and in other regions of the world, and to actively manage ecosystem capacity in all parts of the production chain in order to assure sustainable food production. Is has been proposed that there are three major categories of obstacles to sustainable development: 1) willingness, 2) understanding, and 3) capacity (Gunderson et al. 2002). My thesis has focused efforts on increasing our understanding of current food production systems and
the underlying resources upon which they depend, and emphasizing the importance of links to this support for the design of sustainable food production systems. To this end, I have analyzed cross-scale interactions between food production and ecosystem support made possible by trade and their changes over time. This analysis elucidates connections to ecosystem support not obvious before. I argue that these connections were masked because present indicators do not reflect the globalization of food production. With the term masking I refer to the delinking of social feedbacks from change in ecosystems (Berkes and Folke 1998). I recommend new and improved measures to internalize imported ecosystem support and promote the development of indicators to link food production to ecosystem performance.

Measures to fit globalized production systems and ecological realities

As the examined agricultural and aquacultural production systems became globalized, levels of dependence on other nations’ ecosystems, the number of external supply sources, and the distance to these sources steadily increased. Dependence on other nations is not problematic, as long as we are able to acknowledge these links and sustainably manage resources both at home and abroad. However, the observed measures had not sufficiently expanded analysis beyond the local production site, nor were they directly linked to ecosystem support. Ecosystem subsidies were not recognized or made explicit in national policy or economic accounts. We conclude that trade expanded the observed production systems, but a reliance on old measures kept stakeholders from seeing this.

In Sweden (Paper I), we found that the ArEAs needed for food imports in fact increased in relative importance as total consumption areas decreased, so that by 1994, Swedish consumers needed agricultural areas outside their national borders to satisfy more than a third (35%) of their food consumption needs. As a result, the amount of total consumption satisfied by domestic production decreased from three-quarters to two-thirds. Further, in Paper II, we see that the intensification of Swedish animal production was characterized by a reduction in the use domestic roughages and increased use of manufactured feeds based on imported inputs. So that in 1999, almost 80% of the agricultural support areas needed for these feeds was imported.

That Swedes are not self-sufficient in food production is not necessarily negative. However, to assure sustainable food production and food safety the expansion of the entire production system needs to be recognized. We argue that
presently, this is not the case. In Sweden, official self-sufficiency figures for meat production were estimated as domestic production minus net consumption, i.e., ignoring the large import and export volumes entirely (SCB-JÅ 2002). Another measure under scrutiny was Swedish animal feed statistics (SJV 2000). These state that Sweden produces almost all its own manufactured animal feed for cows, pigs and chickens. This gives the impression of a domestic product, when in fact most of the inputs needed to make the feed are imported. Furthermore, official statistics do not list the country of origin for imports taking place within the EU, but rather the country of purchase. Thus for example, palm kernel oil may be listed as coming from a boreal country (e.g., Germany), when in fact that nation only serves as a middleman.

For Sweden, we recommend several changes that could better illuminate links to external support: a revision of self-sufficiency accounting to include import and export trade flows; an integration of the level of imported inputs in production into measures; and provision of data that allow traceability to the country of origin for products. In addition, a step towards internalizing imported ecosystem support into policy would be to include some measure of external ecosystem support in the national environmental goals (detailed in Paper V). The ArEAs method is one possible measure to quantify this dependency, as it is both ecologically based and has great communicative power.

Trade has also expanded the examined aquaculture production systems. Thailand and Norway have substituted and/or augmented local sources and expanded their supply network across the globe (Paper III). In Thailand, the level of import dependency rises as well as the number of import sources as the aquaculture industry develops between 1980 and 2000. While Thailand utilizes sources from all over the globe, by 2000, this nation was highly dependent on one major supplier, Peru, for 72% of imports by volume. As for Norwegian imports of fishmeal, although import dependency did increase over the entire period, Norway still maintained some level of fishmeal exports between 1980 and 2000. Although there is an increase in the number of fishmeal sources, northern neighbors dominated import trade flows. For both nations, basically four nations (Chile, Peru, Denmark, and Iceland) provide over three-quarters of imports in terms of volume.

We utilized UN sources for our examination of the global trade flows of fishmeal, as historical national data were not readily available. Trade data has just recently been made available free of charge on the website of COMTRADE.
(COMTRADE 2004) that reveals the origin of fishmeal of imports in relation to trade volumes. This database can be considered a first step to allow linking to local ecosystems, however, information as to the particular fish species is lacking here. The major FAO databases (FIGIS 2004, FishStat_Plus 2004) have detailed information as to fish species, but have not yet linked fish imports to country of origin. Further, there is no distinction in statistics as to the use of inputs (i.e., whether it goes to the aquaculture or poultry industries). And no where were we able to find global summaries of the status of fish species used in fishmeal tied to export trade statistics. Although there has been enormous progress in information provision just since I began my studies, it seems that the global market has increased its ability access fishmeal faster than the monitoring agencies capabilities to track and analyze these developments.

Thus, this thesis first proposes a need to develop indicators that can explicitly track flows of inputs to local areas in an ecologically meaningful manner and link them together to more clearly define the production system. I propose that the use of indicators, such as Appropriated Ecosystem Areas, that link consumption and agricultural production systems to imported ecosystem support are a first step. However, these indicators do not help decision-makers to determine if present consumers and future generations are increasing their food security. Nor do they include such large indirect subsidies as fertilizers, pesticides, or machinery that are an integral part of most industrialized production systems. For although current agricultural and aquacultural production methods have indeed generated substantial increases in production levels, if they continue to focus on yield and production increases alone, taking the work of ecosystems for granted, vulnerability can result (Gunderson et al. 1995, Kaspersen and Kasperson 2001). Thus, a second step in the improvement of indicators for resilient food production is to develop measures that comment on ecosystem performance and make explicit any loss of ecosystem capacity.

Recent efforts to ensure ecosystem health have included the move upwards in scale to ecosystem level analysis (Pauly et al. 2003, Pikitch et al. 2004, Schindler 1998) and a recognition of unpredictability and complexity as inherent properties of ecosystems (Levin 1998, Levin 1999). Complex systems thinking creates a shift from assuming that the world is fairly stable and that ecosystem changes can be controlled, to a worldview where nature is dynamic and change is an ongoing process involving uncertainty and unpredictability, and hence cannot be fully controlled (Limburg et al. 2002, van der Leeuw 2000). This has lead to a focus on maintenance of resilience in systems.
Resilience is needed in complex systems to be able to cope with uncertainty and surprise. It provides risk spreading and insurance and sustains options for development (Gunderson and Holling 2002). It has been argued that building resilience in desired ecosystem states is the most pragmatic and effective way to manage ecosystems in the face of increasing environmental changes (Scheffer et al. 2001). Operational indicators of resilience are in development (Carpenter et al. 2001; Millennium Ecosystem Assessment (www.millenniumassessment.org); Gunderson 2000), as discussed in Paper V. We recognize that the development of these indicators for sustainability is not a straightforward task and this thesis has only begun this discussion.

Conclusions

Modern food production is a complex globalized system in which what we eat and how it is produced are increasingly disconnected. This thesis examines some of the ways in which global trade has changed the mix of inputs to food and feed, and how this affects food security and our perceptions of sustainability. In the cases examined in this thesis, food production systems became more globalized over time. This globalization was characterized by an increase in dependency on external support for imports and a stretching of the production chain (Lebel et al. 2002), i.e., increasing both distances to and numbers of input support sources. Because the present global market system is not designed to receive feedbacks as to changes in the ecosystems (Waltner-Toews 1991), I propose that global trade disconnected producers from input supplies and consumers from production (Ekins et al. 1994) and thereby masked ecosystem support. I further propose that masking has reached global proportions today as food production and consumption systems have internationalized.

Again, dependence on other nations is not problematic, as long as we are able to acknowledge these links and sustainably manage resources both at home and abroad. However, ecosystem subsidies are seldom recognized or made explicit in national policy or economic accounts. Masking of local feedbacks can create several potential problems for future food production. This thesis has focused on the first consequence: that we do not recognize our level of dependence on external ecosystem support, and therefore we do not realize we need to be concerned about ecosystem performance there. This has implications for ecosystem performance - unintended effects can take place when consumers are too far removed from the consequences of production and the effects of incorrect
usage can spill out over at large scales or many locations. Provision of appropriate information about external ecosystem support and the production systems of imports could enhance consumer understanding of consequences of changes in consumption (Carlsson-Kanyama and Lindén 2001, Myers and Kent 2003).

Masking can also result in food security issues. I argue that we can be reducing potential future options if we do not actively manage present supply systems for sustainability. Further, if trade is masked at the global level, then this can allow losses of capacity at potentially global scales which implies concerns for world food security. It is time now to start developing indicators that are systemic, dynamic, and that capture ecosystem performance. Further, such indicators need to be embedded in an institutional framework, involving users at several scales that monitor ecosystem performance and reevaluate the indicators with the objective to sustain resilience and ecosystem services or they will be of limited use (Berkes and Folke 1998, Carpenter et al. 2001).

Markets are key institutions today (Chichilnisky 2001). With an improved understanding of ecosystems and the integral role humans have in global ecosystem management, we can improve institutions to better manage and ensure ecosystem performance and resilience (Paper V). Trade has the potential to become an important tool for redistributing resource flows sustainably and closing the ecosystem support gap around the globe. Further, international trade has the potential to provide risk spreading to secure the provision of food. However, at present the increased availability to external natural resources that we have seen in our studies seems to have essentially provided global open access (Dietz et al. 2003, Ostrom et al. 1999), i.e., access without sufficient coupling to consequences and responsibilities. The present international market system was designed for trading goods and maximizing economic efficiency with few dynamic links to ecosystem performance (Daly 1991). Thus, in its present form trade seems to accelerate aforementioned negative ecological changes, affecting resilience and bringing us closer to thresholds in many systems… at same time. However, given the proper framework and incentives, it might also speed up a transition to sustainable production.
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