Rice, fish, and the planet

J. Stephen Lansing[a,b,1] and James N. Kremer[c]

[a]*Stockholm Resilience Centre, SE-10691 Stockholm, Sweden;* [b]*School of Anthropology, University of Arizona, Tucson, AZ 85721-0030; and* [c]*Marine Sciences, University of Connecticut, Groton, CT 06340*

In 2002, the United Nations Food and Agriculture Organization launched a program to recognize "globally important agricultural heritage systems" (1). However, so far, only eight systems have been included (1). In PNAS, the work by Xie et al. (2) reports the results of a 5-yr study of one of the systems, a farming system in south China, where for over 1,200 y, farmers have grown an indigenous species of common carp in their rice paddies. The methods used in this study are impressively thorough, but the purpose of the research is only incidentally to document an exotic agricultural heritage (2). Instead, the main goal is to discover whether features of this traditional agricultural system could contribute to innovations in sustainable agriculture at the global scale by unpacking the ecological interactions between fish, rice, and the environment (2).

The study focuses on two questions: synergies between rice and fish that contribute to high and stable rice yields and the effects of the presence of the carp on the need for chemical inputs (fertilizer and pesticides) (2). Farms in 31 villages in Zhejiang province are randomly selected for a comparative study of rice monoculture vs. rice–fish coculture (2). Later, two experiments are conducted varying pesticide and fish feed while comparing rice monoculture, rice–fish polyculture, and fish monoculture (2). Results indicate that the presence of the fish benefits the rice by reducing insects, diseases, and weeds (2). The researchers notice that, when the fish bump into the rice stems, insects like planthoppers often fall into the water and are eaten (2). Video recordings quantify this effect, indicating a removal rate of planthoppers by fish of about 26% (2). The hitting activity of the fish also shakes dew drops from the plants in the early morning, reducing the risk of spore generation and mycelium penetration of rice blast disease in the leaves. The carp also eat or uproot many weeds, resulting in an almost weed-free paddy (2).

If the fish are beneficial to the rice, the converse is also true. The presence of the rice plants attracts insects, which become a food source for the fish, and the leaves of the plants provide shade that reduces water temperature in the hot season. Rice also moderates the aquatic environment. It acts as a nitrogen sink and helps reduce the concentration of ammonia in the water and total N in the soil. Overall, paddies with fish require 68% less pesticide and 24% less fertilizer than rice monoculture.

Fig. 1. Rice terraces of Zhejiang, China. Modified from Xie et al. (2).

As Xie et al. (2) note, the wider significance of these results has to do with the global importance of rice agriculture, both as a source of food and because of the large and growing impact of fertilizers and pesticides on the environment. Rice–fish cocultures are not unique to China but have been reported in Egypt, India, Indonesia, Thailand, Vietnam, the Philippines, Bangladesh, and elsewhere (3, 4). Today, rice is the main ingredient in the daily diets of about 3 billion people. More than 90% of worldwide rice production occurs in developing nations, which are also the regions with the highest rates of population growth, and therefore, rice production is expected to increase (5). However, paddy rice is also the leading agricultural source of greenhouse gases, partly because of excess fertilizers but also because of the unique ability of rice paddies to pump methane into the atmosphere. When paddies are submerged, methanogenic bacteria become active, and the rice stalks enable the gas to vent into the atmosphere. This effect is unique to rice. Currently, methane accounts for about 20% of the global greenhouse effect, of which about one-half comes from flooded rice paddies (6). As a greenhouse gas, methane is ∼25 times more potent than carbon dioxide (7). However, this finding underestimates the contribution of methane to the climate problem, because its interaction with aerosols increases its activity; also, its relatively short residence time in the atmosphere makes it especially sensitive to corrective intervention (8). There is also a synergistic effect, because increased amounts of atmospheric CO_2 are predicted to stimulate methane emissions from rice paddies (9). Because the soil methanogens quickly become dormant when the paddies are drained, emissions can be reduced by decreasing the amount of time that the paddies are submerged. However, this method has not been widely adopted.

The overfertilization of rice with nitrogen also releases another greenhouse gas, nitrous oxide, which is roughly 300 times more potent than CO_2 and also depletes stratospheric ozone. Enormous quantities of excess nitrogen fertilizer have been applied to rice paddies since the 1970s (10). Why excess? Beginning in the 1970s, fast-growing hybrid Green Revolution rice seeds replaced slower-growing native rice varieties in much of Asia. The nitrogen requirements of traditional rice were satisfied by symbiosis with nitrogen-fixing bacteria supplemented by organic manure. However, the new rice required chemical fertilizers. To achieve rapid results, nations like Indonesia created crash programs to produce enormous quantities of nitrogen and phosphate fertilizer, which were sold to farmers at deeply discounted prices. Typically, all of the nitrogen and phosphate needed for each crop cycle was supplied to the farmers on credit. The cost of these inputs was deducted from the payment to the farmer when the crop was sold.

In Indonesia, average grain yield rose from 1.53 ton ha^{-1} in the 1960s to 4.2 ton ha^{-1} in 2000 (11). However, much of the fertilizer was not used by the plants. A recent study used changes in the ratio of stable nitrogen isotopes to investigate the health of coral reefs around the island of Bali. Offshore from agricultural drainages, cores taken from *Porites* coral track a massive increase in N fertilizer coinciding with the onset of the Green Revolution in the 1970s (12). Obviously, none of the N fertilizer that wound up on the reefs was used by the rice. The same is true of phosphate, a mineral that is abundant in the volcanic soil of Bali, as it is in most of Indonesia. Phosphate leached from the landscape by the rains is conveyed to the paddies in centuries-old irrigation canals, replenishing the paddy soil. Consequently, most of the phosphate

Author contributions: J.S.L. and J.N.K. wrote the paper.

The authors declare no conflict of interest.

See companion article 10.1073/pnas.1111043108.

[1]To whom correspondence should be addressed. E-mail: lansing@santafe.edu.

fertilizer added to the paddies is unnecessary. Direct measurements of PO_4 in irrigation waters showed that nearly all of the phosphate fertilizer washes out of the paddies and into the rivers, accumulating to very high levels before reaching the coast (13).

In Europe and North America, soils are routinely monitored, and fertilizer application rates are adjusted to local conditions. However, in much of the tropics, soil testing is sporadic at best. Globally, the application of nitrogen fertilizer increased from 32 million metric tons in 1970 to around 80 million metric tons in 1990, and it is predicted to increase to 130–150 million metric tons by 2050 (14). Eutrophication from nitrogen loading has been identified as arguably the most serious anthropogenic threat to coastal waters worldwide (15, 16). However, the International Rice Research Institute estimates that, in each of the next 20 y, the world will need an additional 8–10 million tons of rice more than in the previous year to meet expected needs (17). So what is to be done?

The work by Xie et al. (2) uses Green Revolution rice monoculture as a baseline from which to examine the role of ecosystem services in an ancient polyculture (2). Their method is a side by side comparison of hundreds of Green Revolution paddies paired with fields growing the same high-yield rice varieties with the traditional rice–fish polyculture (2). The key finding is that the rice–fish polyculture exploits synergies between species to dramatically reduce the need for chemical inputs while sustaining high and stable grain production. As Xie et al. (2) observe, so far, such positive interactions and complementary use of resources between species have largely been ignored by agricultural researchers (3). Their work offers a model for integrating a broader ecological and evolutionary perspective into research on rice in the tropics (2). Their analysis of fertilizer and fish feed in aquatic nitrogen cycles suggests studies to quantify possible reductions in nitrous oxide production by denitrification when N inputs can be minimized in rice paddies (2). Similarly, their findings on the behavioral interaction of fish dislodging insects raise questions of adaptive interactions among predators and prey (2). Classic studies of fish–copepod interactions showed that "simple" arthropod prey changed their behavior in response to the presence of predators, even when prey were safe in a refuge (18). Recently, changes in rice growing practices have been offered as partial explanation for a temporary decline in atmospheric methane late in the 20th century (19). In the paddies studied by Xie et al. (2), chemical fertilizers were used, so methane reductions were likely even with the fish–rice system.

Rice–fish polyculture exploits synergies between species to dramatically reduce the need for chemical inputs.

Before the Green Revolution in rice, complex nutrient pathways linking many species made traditional rice paddies the most productive agroecosystem from the standpoint of energy efficiency. In 1970, when the world population stood at 3.5 billion, Norman Borlaug accepted the Nobel Peace Prize for his role in launching the Green Revolution and predicted that it could buy the world a generation's breathing space in which to solve the equation of food and population growth (20). Today, as we pass the 7 billion milestone, the promised increase in grain production has been achieved, but the anthropogenic uses of nitrogen now exceed those uses of all natural systems (21), pesticide use has caused serious environmental problems, and genetic diversity of food crops like rice has been drastically reduced. The work by Xie et al. (2) makes a strong case that the ecological legacy of traditional agricultural polycultures offers important lessons for the development of more sustainable agriculture. Perhaps we are on the verge of a new emphasis on *ecosystem-based agriculture* fostered by an ecosystems perspective in research, much as *ecosystem-based management* has become standard in other areas of environmental science.

1. Food and Agriculture Organization of the United Nations (2011) *Globally Important Agricultural Heritage Systems (GIAHS).* Available at http://www.fao.org/nr/giahs/en/. Accessed November 10, 2011.
2. Xie J, et al. (2011) Ecological mechanisms underlying the sustainability of an agricultural heritage rice–fish coculture system. *Proc Natl Acad Sci USA*, 10.1073/pnas.1111043108.
3. Frei M, Becker K (2005) A greenhouse experiment on growth and yield effects in integrated rice-fish culture. *Aquaculture* 244:119–128.
4. Datta A, Nayak DR, Sinhababu DP, Adhya TK (2009) Methane and nitrous oxide emissions from an integrated rainfed rice-fish farming system of Eastern India. *Agric Ecosyst Environ* 129:228–237.
5. Frei M, Becker K (2005) Integrated rice-fish culture: Coupled production saves resources. *Nat Resour Forum* 29:135–143.
6. Robin M, Wassman R (2003) Modeling the impacts of climate change and methane emission reductions on rice production: A review. *Eur J Agron* 19:573–598.
7. Forster P, et al. (2007) *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge University Press, Cambridge, UK), 129–234.
8. Shindell DT, et al. (2009) Improved attribution of climate forcing to emissions. *Science* 326:716–718.
9. van Groenigen KJ, Osenberg CW, Hungate BA (2011) Increased soil emissions of potent greenhouse gases under increased atmospheric CO_2. *Nature* 475:214–216.
10. Socolow RH (1999) Nitrogen management and the future of food: Lessons from the management of energy and carbon. *Proc Natl Acad Sci USA* 96:6001–6008.
11. Fuglie KO (2004) Productivity growth in Indonesian agriculture, 1961–2000. *Bull Indones Econ Stud* 40:209–225.
12. Marion GS, et al. (2005) Coral skeletal delta(15)N reveals isotopic traces of an agricultural revolution. *Mar Pollut Bull* 50:931–944.
13. Lansing J, et al. (2001) Volcanic fertilization of Balinese rice paddies. *Ecol Econ* 38:383–390.
14. Matson PA, Naylor R, Ortiz-Monasterio I, I (1998) Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* 280:112–115.
15. Valiela, et al. (1992) Understanding changes in coastal environments: The LMER Program. *Eos (Washington DC)* 73:481–485.
16. Vitousek P, et al. (1997) Human alteration of the global nitrogen cycle: Sources and consequences. *Ecol Appl* 7:737–750.
17. International Rice Research Institute. Available at http://irri.org/news-events/hot-topics/international-land-acquisition-for-rice-production?print=1&tmpl=component. Accessed November 10, 2011.
18. Bollens SM, Frost BW (1991) Diel vertical migration in zooplankton: Rapid individual response to predators. *J Plankton Res* 13:1359–1365.
19. Fuu K, et al. (2011) Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. *Nature* 476:194–197.
20. Norman Borlaug—Nobel Lecture. Available at http://www.nobelprize.org/nobel_prizes/peace/laureates/1970/borlaug-lecture.html. Accessed November 10, 2011.
21. Galloway JN, Cowling EB, Seitzinger SP, Socolow RH (2002) Reactive nitrogen: Too much of a good thing? *Ambio* 31:60–63.