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ANALYSIS

Volcanic fertilization of Balinese rice paddies

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Abstract

Since the advent of high-yielding "Green Revolution" rice agriculture in the 1970s, Balinese farmers have been advised to supply all the potassium and phosphate needed by rice plants via chemical fertilizers. This policy neglects the contribution of minerals leached from the volcanic soil and transported via irrigation systems. We documented frequent deposition of volcanic ash deposits to rice producing watersheds. Concentrations of phosphorus in rivers were between 1 and 4 mg l^{-1} PO_4, increasing downstream. We measured extractable potassium and phosphate levels in the soils of unfertilized Balinese rice paddies, and found them to be indistinguishable from those in fertilized paddies, and sufficient for high grain yields. Field experiments varying phosphorus applications to rice fields from 0 to 100 kg superphosphate per hectare (7–26 kg P ha^{-1}) demonstrated small increases in harvest yields only with the smallest additions. Direct measurements of PO_4 in irrigation waters indicate that most of the added phosphate flows out of the paddies and into the river systems, accumulating to very high levels before reaching the coast. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Balinese farmers have long regarded volcanoes as homes of the goddesses who bring fertility to

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their fields. Nutrient-rich volcanic soils combined with microbial nitrogen fixation and traditional harvest methods that left much of the plants in the fields meant that farmers growing traditional slow-maturing rice varieties could escape the need to fertilize their rice paddies. But following the introduction of fast-growing high-yield 'Green Revolution' rice in the 1970s, Indonesian farmers have been encouraged to add all necessary nutrients in the form of chemical fertilizers to their rice paddies. Indonesia has invested heavily in fertilizer production facilities and has provided substantial subsidies for fertilizer use since the 1970s, with maximum retail prices for P and K never more than half the world price. Fertilizer subsidies 'constitute a significant financial burden to the government' (Roche, 1994).

Significantly, the recommendations for fertilization were made without taking into account the potential contribution of natural sources (Roche, 1994, p. 63). In 1998, all Indonesian paddy rice farmers (including the Balinese) were urged by the Ministry of Agriculture to add 33 kg phosphorus [added as 125 kg $Ca(H_2PO_4)_2$, SP-36 'super-phosphate,' equivalent to 101 kg PO_4] and 100 kg potassium (as KCl) per hectare of rice paddies for each rice crop (Indonesian Ministry of Agriculture, 1998). In Bali, usage lags below this target. Actual usage in 1998 was 3 448 000 kg SP-36 on 155 304 ha of paddies, equivalent to 5.9 kg P ha^{-1} (or 18 kg PO_4 ha^{-1}).

Our research presented here indicates that phosphate and potassium are continuously leached from the volcanic soil by rainfall, and delivered to rice paddies by irrigation systems in quantities sufficient for abundant rice harvests. The superfluous P fertilizer applied by the farmers for the past three decades washes directly into the rivers, representing a significant ecological threat to waterways and perhaps coastal waters, as well as a certain economic burden on the farmers.

2. Methods

Volcanic ash in paddy soils was obtained by manual metal corers with plastic liners to depths of up to 5 m. Ash layers were identified visually. Additionally, ash samples near the caldera of Mt. Batur were collected by hand for nutrient analysis. Paddy soil was collected, dried and analysed. Soil and ash nutrient analyses were carried out by lAS laboratories (Phoenix AZ 85034) using the Olsen Bicarbonate test for available phosphate and the ammonium acetate method for available potassium (Council on Soil Testing and Plant Analysis, 1992).

Flow and nutrient concentrations were measured at biweekly intervals at the Oos, Petanu, Empas, Ayung, Ho and Buleleng rivers. Average flow rates were estimated in irrigation canals with Global Water Flow Probe Model FPO 1. Flow was measured for 1 min intervals at up to five points in the cross-section, and averaged. An additional survey of dissolved phosphate concentrations was done at various elevations in the Bangli and Gianyar regencies of southeast Bali during July 8–15, 1997.

For dissolved nutrients, water samples >250 ml were collected in plastic bottles well rinsed with sample and were analyzed within 4 h. Triplicate 10 ml aliquots were filtered through glass fiber filters (GF/C) to remove particulates. Dissolved reactive phosphorus was measured colorimetrically using prepared chemical packets (HACH method #8048) read on a HACH Model DR 890 colorimeter. The HACH method is internally standardized, but in addition, we calibrated our analysis in the field with prepared standard solutions of PO_4. Field samples yielding high concentrations (>2.5 mg l^{-1}) were also analyzed after 10:1 dilution with clean water of known PO_4 concentration.

Agricultural experiments were conducted in three sites, two in south Bali in the vicinity of Sengkidung, Klungkung and one in north Bali in Busungbiu, Buleleng during September–December 1998. Farmers were paid to participate in a blind experiment in which we varied the amount of phosphate fertilizer applied to their fields. Fertilizer application, irrigation flows, and harvest yields were recorded, and soil and nutrients were analyzed at each site. Phosphate concentrations were measured in water samples from the irrigation inflow and outflow at biweekly intervals, plus on the day before and the day after planting and fertilizer addition. Superphosphate, $Ca(H_2PO_4)_2$, was applied to two replicate paddy fields in each site at three test levels: 25, 50, and 100 kg ha^{-1} (representing 7, 13, and 26 kg P ha^{-1}). As controls, two replicates at each site had no phosphate addition. Following current recommendations, phosphate was applied immediately before planting as top-dressing. High-yielding rice seedlings were planted, and irrigation water was let into the fields. The water levels were allowed to rise slowly to a depth of 5 cm in 2–3 days. Along with experimental treatment levels of P, additional fertilizer was applied to all plots at the currently recommended rate of 220 kg of urea and 100 kg KCl ha^{-1}.

3. Results

3.1. Volcanic geochemistry and mineral leaching

Balinese volcanoes are part of the Sunda-Banda arc, a continuous geological structure that extends for approximately 4700 km from the northern tip of Sumatra in the west to the island of Nila in the east (Wheller et al., 1987). In recent times, there have been two active volcanoes on Bali, Mount Agung and Mount Batur. The formation of the Batur caldera circa 23 670 ± 210 y. B.P. deposited a mineral-rich ignimbrite layer over most of southern Bali[1], which became the Balinese 'ricebowl', with irrigated rice terraces developing by the eighth century AD. A summary in 1986 reported that Mount Batur has erupted in 1804, 1821, 1849, 1854, 1888, 1897, 1904, 1905, 1921, 1922, 1923, 1924, 1925, 1926, 1963, 1965, 1966, 1968, 1970, 1971, 1972, 1973, and 1974 (Wheller and Varne, 1986). Mount Batur continues to exhibit frequent eruptions. While not all eruptions produce ash deposits on distant rice paddies, many do, as is evident from soil cores of paddies in the village of Sebatu, 20 km south of the caldera (Fig. 1). Samples of volcanic ash from Mount Batur averaged 16 ppm PO_4 and 1.8 ppm K at pH 4.3.

[1] An ignimbrite layer is formed when hot airborne volcanic ash melds with existing rock; the resulting layer has significant amounts of air trapped between its layers, thus making it more vulnerable to weathering.

3.2. Nutrients in soils and water

High concentrations of dissolved reactive phosphate were measured in all samples of river water, and a downstream gradient in PO_4 levels was clearly evident (Fig. 2). While water in the volcanic crater lake of Mount Batur measured only 0.4 ppm PO_4, water flowing from springs into surface streams at elevations near the beginning of irrigation farming averaged 1.5 ± 0.2 ppm PO_4 (Fig. 2).

We measured potassium in soil but not in irrigation flows. Observed mean levels in Balinese paddies were 271 ppm K, in a sample including eight fields where the farmers reported that P and K fertilizer had not been applied for at least 10 years (Fig. 3).

3.3. Field experiments in P replenishment

Experimental additions determined direct effects of the phosphate fertilizer applied by the farmers. Minor differences in rice yields were measured with phosphate applications from 0 to 100 kg ha^{-1} (Fig. 4). Two-factor ANOVA inden-tified both site and phosphate addition as significant. The sites in North Bali were systematically lower. Slight increases in yields occurred in plots that received 25 kg ha^{-1} fertilizer, which showed an average

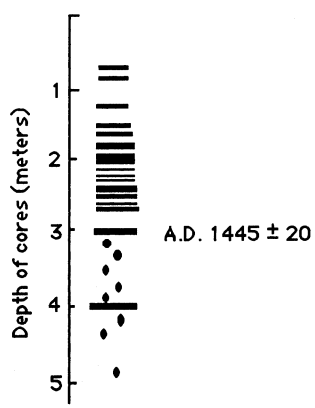

Fig. 1. Volcanic ash deposits in soil cores from Sebatu, 20 km south of Batur caldera. Thin lines indicate 20–30% pumice; thick lines indicate > 50% pumice; dots indicate weathered pumice. A radiocarbon date was obtained at 3 m. depth. The absence of visible ash deposition in the upper core is attributable to anthropogenic disturbances.

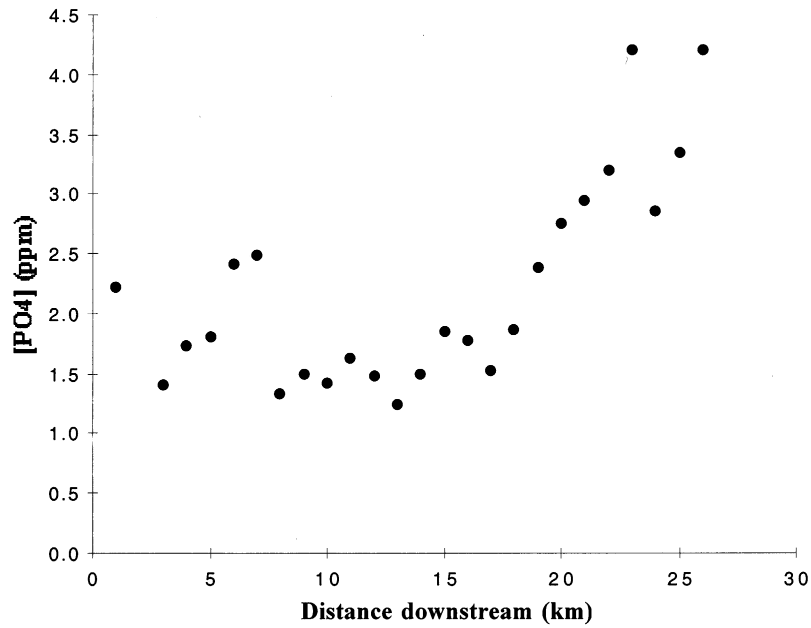

Fig. 2. Dissolved reactive phosphate (PO_4) measured in spring and river water showed a pattern of increasing concentration downstream from river headwaters in the Bangli and Gianyar regencies of southeast Bali (July 1997).

harvest increase of 15% over those that received no fertilizer. No additional response occurred at the 50 and 100 kg levels; indeed, plots that received 50 kg treatments showed only 9% improvement over those that received no added phosphate.

We also measured the amount of dissolved PO_4 in the irrigation water entering and leaving each paddy field, at biweekly intervals around planting (Fig. 5). The outflow after fertilization from plots receiving 25 kg of fertilizer was 6.25 ± 4.6 ppm of PO_4. Phosphate levels were very similar in all paddies at all sampling times except for large spikes in the outflows immediately after fertilization. It appears that much of the phosphate washes out of the paddies soon after it is applied, evidence that the paddy ecosystem has reached absorption capacity.

4. Discussion

4.1. Volcanic geochemistry and mineral leaching

Samples of volcanic ash from Mount Batur contained significant amounts of phosphorus and potassium that are susceptible to leaching. The deposition of volcanic ash at frequent intervals, together with weathering caused by wind and rain, gradually and continually replenish soils with these nutrients. Tropical rains leach minerals from the glassy and pumiceous ignimbrite rock.

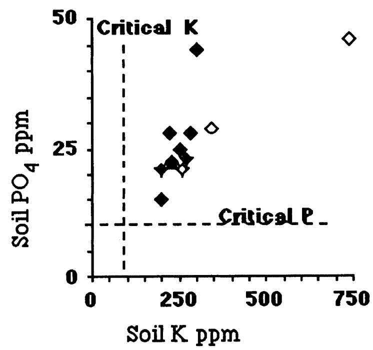

Fig. 3. Available P and K in 11 rice paddies from Kecamatan Tegallalang, south-central Bali. Solid symbols denote fields that have not received P or K fertilizer in at least a decade; open symbols denote fields that have been fertilized semi-annually. Critical levels are the threshold beyond which additional fertilization does not affect growth (Greenland, 1997).

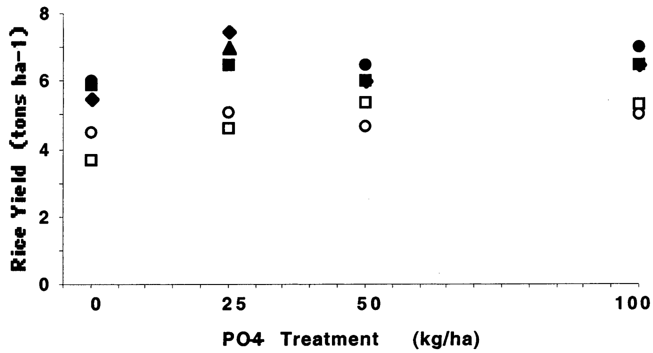

Fig. 4. Variation in rice harvests by phosphate treatment. Replicates from two paddies in north Bali (open symbols) were consistently lower than the replicates at four fields in south Bali (dark symbols). Increases in yield (15%) occurred between zero addition controls and the lowest treatment; phosphate additions above 25 kg/ha produced negligible additional increases in yield.

Our direct measurements confirm high concentrations of dissolved phosphate in both springs and river waters. Thus, the hundreds of small-scale irrigation systems that capture the flow from streams, rivers and springs are transporting dissolved minerals directly to the fields. As a result, water used for irrigation provides a direct pathway for fertilization of irrigated rice. Rice paddies have plough pans that trap water and nutrients, creating pond-like aquatic ecosystems where erosion and percolation (and thus loss of nutrients) are minimized. The direct transfer of dissolved P to the plant's roots is a very efficient 'hydroponic' mechanism for fertilization. In addition, the continuous flow of irrigation water during the growth interval replenishes P, as well as K and other trace minerals in the soil.

4.2. Nutrients in soils and water

A key question is thus whether the quantities of nutrients borne by the irrigation water are sufficient to sustain high yields of grain. A rough mass balance calculation suggests so. For 2 years, we have monitored irrigation flows, rice yields and nutrient loads in numerous sites around the island. Values of PO_4 for rivers and irrigation canals average 2.3 ± 0.8 ppm (0.8 g P m^{-3}), with the highest values observed at the mouths of rivers near the coast. The mean irrigation flow is 3.5 ± 1.6 l s^{-1} ha^{-1}, which would deliver 63 ± 29 kg PO_4 ha^{-1} (21 kg P ha^{-1}) in a 90-day growing season. The average observed phosphorus removal in irrigated rice systems in Asia is 3 kg P per ton of grain yield (personal communication: Achim Doberman, International Rice Research Institute, Los Banos, Philippines). With 7 tons ha^{-1} grain considered a high yield, 21 kg P ha^{-1} would be removed. Thus, average flows of irrigation water deliver adequate P, above and beyond the extractable P in the paddy soils, which is also substantial. Additionally, the amount of P required for a given yield depends on harvest practices. While 21 kg P ha^{-1} are required to grow a crop of 7 tons ha^{-1}, 7 kg P are returned to the paddy if the straw is left in the field after harvest, as is the practice in traditional Balinese fields. The phosphorus remaining in the field in stalks might be expected to approach a steady state, resulting in a net demand of 14 kg P ha^{-1} (A. Doberman, pers. commun.).

This budget may be summarized as follows:

We can estimate independently the P exported from our direct measurements in experimental fields following fertilization (see Fig. 5). Outflow concentrations elevated to 5–7 ppm PO_4 were measured the day after application. Average flow rates of 3.5 l s^{-1} ha^{-1} would export 0.5–0.7 kg P ha^{-1} d^{-1}. If the outflow remained at this concentration for about a week, our measurements account for a rapid loss of up to 3.5–4.8 kg P ha^{-1}. For all treatment levels, outflow concentrations after the initial peak were 2 ppm PO_4, accounting for another 16 kg P ha^{-1} lost over the remaining 83 days, for a total measured export of about 20 kg P ha^{-1}. This is comfortably within the estimate from the budget above, and represents 70 to > 100% of the added SP-36. There is substantial uncertainty in all these calculations, especially since the duration of the initial pulse is not certain, but there is little doubt that a substantial fraction of added phosphate fertilizer is lost directly in outflowing irrigation waters.

Still, irrigation waters now presumably have higher levels of PO_4 than would be the case if all farmers stopped using PO_4 fertilizer. If fertilization ended and PO_4 levels dropped to the quantities observed in upland springs (1.5 ppm PO_4), then low flows (1.9 l s^{-1} ha^{-1}) would deliver 7 kg P ha^{-1} in a 90-day growing season, approximately half the net requirement for the grain yield.

For the past three decades, agricultural policy has assumed that all of these nutrients must be replenished by chemical fertilizers, not oniy for Bali, but for all rice growing areas of Indonesia (Indonesian Ministry of Agriculture, 1995). Our results suggest the contrary, that volcanic replenishment of P and K via irrigation flows is sufficient or nearly sufficient for rice agriculture. For comparison, PO_4 concentrations in the Oos and Petanu rivers of Bali average over 2 ppm soluble PO_4 in the dry season, while return flows from heavily fertilized irrigated fields in the San Joaquin Valley of California average 0.3–1.2 ppm of soluble PO_4 (Dunne and Leopold, 1979). Similarly, levels of potassium extracted from unfertil-

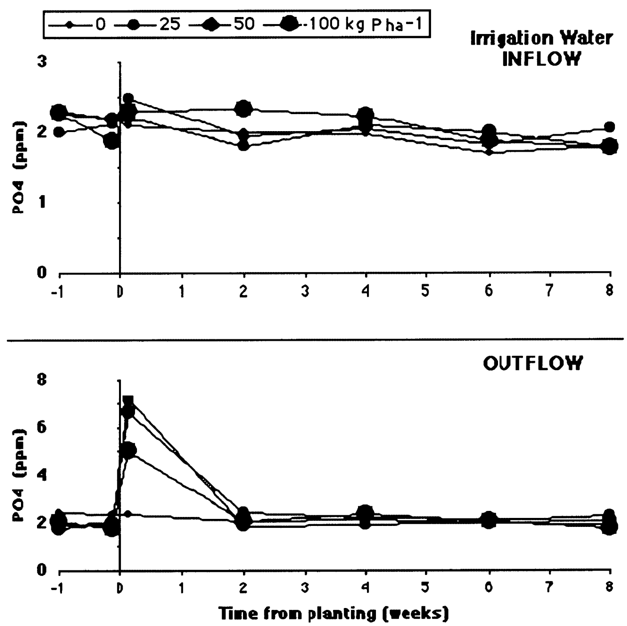

Fig. 5. PO_4 in irrigation water flowing into and out of test plots. Fertilizer was applied immediately before planting. Base levels of inflow and outflow average 2.0 ± 0.1 ppm except immediately after fertilization.

ized Balinese soils were high, often 250 ppm. Response to potassium fertilizer occurs below 80 ppm (Greenland, 1997).

4.3. Field experiments in P replenishment

In the controlled agricultural experiments, the consistency among replicate fields as well as across the different localities was notable. Above the first treatment level (25 kg PO_4 ha^{-1}), differences in yield were not consistent with a fertilization effect. A small increase in yield was observed with the lowest treatment addition of P fertilizer, however, so the practice of slight phosphate additions may be worthwhile where the tradeoff between fertilizer cost and a 10–15% improvement in yield is advantageous, but the environmental cost of higher nutrient loading should also be noted since most of the fertilizer flows into the river system. There appears to be no benefit to fertilizing at near the recommended dose.

4.4. Implications

Our analysis conducted on dry soil and in river and irrigation water using standard techniques show a balanced system with levels of nutrients exceeding those needed by the rice crop under flooded conditions. These results suggest that flushes of nutrients with pH levels approaching neutrality should provide the young rice transplants with an ideal growing environment at the onset of the growing season, with P and K sufficient for luxury consumption. Bali is a small island, but there is reason to believe that similar conditions may be typical of rice paddies along the Sunda-Banda volcanic arc, and perhaps elsewhere. The mineral composition of Indonesian volcanic rock is broadly similar across the archipelago, with progressively more K-rich volcanoes from west to east (Wheller et al., 1987). The availability of mineral nutrients to the plants is influenced by several additional environmental factors besides the composition of the rock, such as relatively constant high temperatures and high rainfall. These factors are common to the rice-growing regions of the archipelago.

In addition, there are cultural factors sustaining high levels of nutrients in paddies. Like most Indonesian farmers, Balinese traditionally thresh the rice stalks in situ and remove only the grain, leaving the rest of the plant to be plowed under or burned, retaining most nutrients. The phosphorus removed by harvest appears to be replenished by the supply in irrigation flow in Balinese paddies, and additional extractable nutrients are available in the soils. This may help to explain the similarity of P levels in both fertilized and unfertilized paddies. Where harvest practices involve removal of more of the plant, fertilization may be required.

But at present, very high concentrations of phosphate are entering the Balinese coastal ocean. No systematic study of the health of coral reefs in Bali has yet been conducted, but the World Wildlife Fund office in Bali reports that red tides are frequently observed (Dr. Timothy Jessup, pers. commun.). Further, a recent preliminary investigation surveyed the condition of reefs lining the coast where rivers draining the intensively fertilized region of Gianyar. These reefs have few if any growing coral colonies and often abundant growths of macroalgae and destructive grazing fauna (Kremer et al., 2000).

From a larger perspective, the institutional recommendations to add unneeded fertilizer reveal the tendency for governments to respond to foreign pressure for energy- and resource-intensive industrial practices, in this case, support of the agro-chemical industry. The farmer in the field is ill positioned to overrule these recommendations unless they receive more balanced information. When so informed, however, they respond rationally. Following discussion of our experimental phosphate addition results, 17 groups of farmers (Balinese ‘subaks’) have modified their practices, and of their own accord are applying less phosphate fertilizer (Lansing, unpublished).

The over-fertilization of Balinese rice paddies adds excess quantities of P to an island ecology that has already been damaged by the application of chemical pesticides, as noted in a 1988 World Bank study (Machbub et al., 1988). Elsewhere, we have shown that the planned introduction of pesticides bypassed a more effective and relatively cost-free traditional method of pest control, based on the control of irrigation flows (Lansing and Kremer, 1993). By synchronizing irrigation schedules and planting the same rice varieties over large areas, Balinese farmers deliberately induce region-wide fallow periods. The paddies are dried for harvest, left fallow and then flooded for the next planting cycle, depriving most pests (rats, insects and insect-borne diseases) of their habitat. Computer simulation modeling suggests that this system of region-wide pest control is self-organizing if left alone (Lansing et al., 1998). To prevent further costly errors in agricultural and environmental policy, the extent and significance of such self-sustaining agro-ecological processes merit further investigation.

Acknowledgements

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References

Sd, L., 1992. Reference Methods for Soil Analysis. Council on Soil Testing and Plant Analysis, Athens, GA.

Dunne, T., Leopold, L.B., 1979. Water in Environmental Planning. W.H. Freeman, New York, p. 757.

Greenland, D.J., 1997. The Sustainabilitv of Rice Farming. CAB International, New York, p. 131.

Indonesian Ministry of Agriculture, 1995. Head of the Bureau of Wet Rice Agriculture Decision Document 18. (Surat Keputusan Menteri Pertanian/Ketua Badan Pengendali Bimas No. 1 8/SK/Mentan/Bimas/I/1985).

Indonesian Ministry of Agriculture, 1998. Head of the Bureau of Wet Rice Agriculture Decision Document 5. (Surat Keputuas Menteri Republik Indonesia/Ketua Badan Pengendali Bimas No: 05/Kpts/Mentan/Bimas/X/1998).

Kremer, J.N., Murphy, R.C., Lansing, J.S., Kremer, P., 2000. Bali's Reefs: A Qualitative survey and Potential inputs of land-derived nutfients. Report to the World Wide Fund for Nature (WWF) in Indonesia. Unpublished report.

Lansing, J.S., Kremer, J.N., 1993. Emergent Properties of Balinese Water Temples. Am. Anthropol. 95 (1), 97–114.

Lansing, J.S., Kremer, J.N., Smuts, B.B., 1998. System-dependent selection, ecological feedback and the emergence of functional structure in ecosystems. J. Theor. Biol. 192, 377–391.

Machbub, B., Ludwig, H.F., Gunaratnam, D., 1988. Environmental Impact from Agrochemicals in Bali (Indonesia). Environ. Monitor. Assess. 11, 1–23.

Roche, F.C., 1994. The technical and price efficiency of fertilizer use in irrigated rice production. Bull. Indo. Econ. Stud. 30 (1), 59–83.

Wheller, G.E., Varne, R., 1986. Genesis of dacitic magmatism at Batur volcano, Bali, Indonesia: implications for the origins of stratovolcano calderas. J. Volcanol. Geotherm. Res. 28, 363–378.

Wheller, G.E., Varne, R., Foden, J.D., Abbot, M.J., 1987. Geochemistry of quaternary volcanism in the Sunda-Banda Arc, Indonesia, and three-component genesis of island-arc basaltic magmas. J. Volcanol. Geotherm. Res. 32, 137–160.