Current Anthropology Volume 44, Number 3, June 2003

Rainfall Variability and Subsistence Systems in Southeast Asia and the Western Pacific[1]

by Robert E. Dewar

Subsistence systems in insular Southeast Asia and the western Pacific are geographically patterned: from west to east, grain crops disappear while root and tree crops become more important, and south of the Torres Strait no crops are grown. Previous explanations for these patterns have assumed either a historical cause (the expansion of root and tree crops before grain crops) or some form of environmental filter. Paralleling the agricultural pattern is a west-to-east pattern of increasing variability in interannual rainfall variation. I propose that this variability limited the utility of annual crops and increased reliance on long-lived plants whose food production averages across longer periods. The range of human responses to these difficult conditions is illustrated by discussion of the anomalies represented by the unique qualities of the agricultural regimes of Botel Tobago and eastern Melanesia and by the distribution of crops and subsistence systems across the Torres Strait.

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The geographical patterning of subsistence systems and agricultural crop species in Southeast Asia and the western Pacific has been explained in terms of two different sorts of causes: events in human history reflecting domestication, diffusion, migration, and isolation or environmental differences or "filters." While historical factors are certainly important, a hitherto undescribed environmental feature—interannual rainfall variability—may be of crucial importance in understanding this patterning.

In the Asian and Pacific Tropics, the primary means of subsistence is nearly everywhere the cultivation of crops in fields. There are three main exceptions: (1) None of the historic or prehistoric Aboriginal peoples of mainland Australia engaged in agriculture, so far as we know. (2) Although most of the peoples of New Guinea cultivated crops, some lowland groups were primarily dependent upon harvesting sago palm (*Metroxylon* spp.) starch. (3) In some low islands of Micronesia, the primary staple was the tree crop screw pine (*Pandanus* spp.) (Barrau 1962), and on some islands in the Malukus, the Solomons, and the Bismarck Archipelago there was heavy reliance on a varied suite of tree crops (Latinis 2000, Lepofsky 1992, Yen 1974*a*).

The absence of field cultivation in Australia has attracted the most attention from anthropologists and archaeologists (for recent reviews, see Frankel 1995, Harris 1995, Yen 1995). Jones and Bowler (1980:24) offered an environmentally based argument, suggesting that before the flooding of the Torres Strait a wide savanna served as a barrier to the southward spread of agriculture and subsequently the sea may have served as the barrier. Diamond (1998) has proposed that northern Australia was environmentally unsuited to agriculture because of infertile soils and climatic variability related to the El Niño/Southern Oscillation. Whether the Torres Strait functioned as a barrier was the focus of a major research effort by David Harris (1977, 1979, 1995), who concluded that "it has functioned neither as a barrier to, nor as a bridge for, the 'transmission' of agriculture into Australia" (1995:854). I will argue that an environmental filter did limit the southward expansion of agriculture below the Torres Strait but, in agreement with Harris, that the strait itself had little to do with it.

The geographical distribution of crops in Southeast Asia and the western Pacific has usually been interpreted as a product of historical processes, most famously by Carl Sauer, whose 1952 monograph has long had great influence (Spriggs 1982*b*). Under this kind of explanation, the most widely distributed crops are assumed to have had the greatest amount of time to spread, the less extensive geographical spread of other crops being taken as evidence that they are more recent introductions. Figure 1 shows a progressive reduction in the variety of grains from west to east. Although a number of important crops were domesticated on or near New Guinea, the apparent origins of some of the crops of the region are to be found on or near the Asian mainland (Yen 1973, 1991, 1995). This is certainly true for rice, the millets, Job's tears, some yams, and Eumusa bananas and pos-

1. I thank Jim Wallis for teaching me how to employ the L-moments method. I greatly appreciate, though I did not always heed, the criticisms and suggestions of Hal Conklin, Roy Ellen, Pat Kirch, Alison Richard, John Terrell, Henry Wright, and several anonymous reviewers. [Supplementary material appears in the electronic edition of this issue on the journal's web page (http://www.journals.uchicago.edu/CA/home.html).]

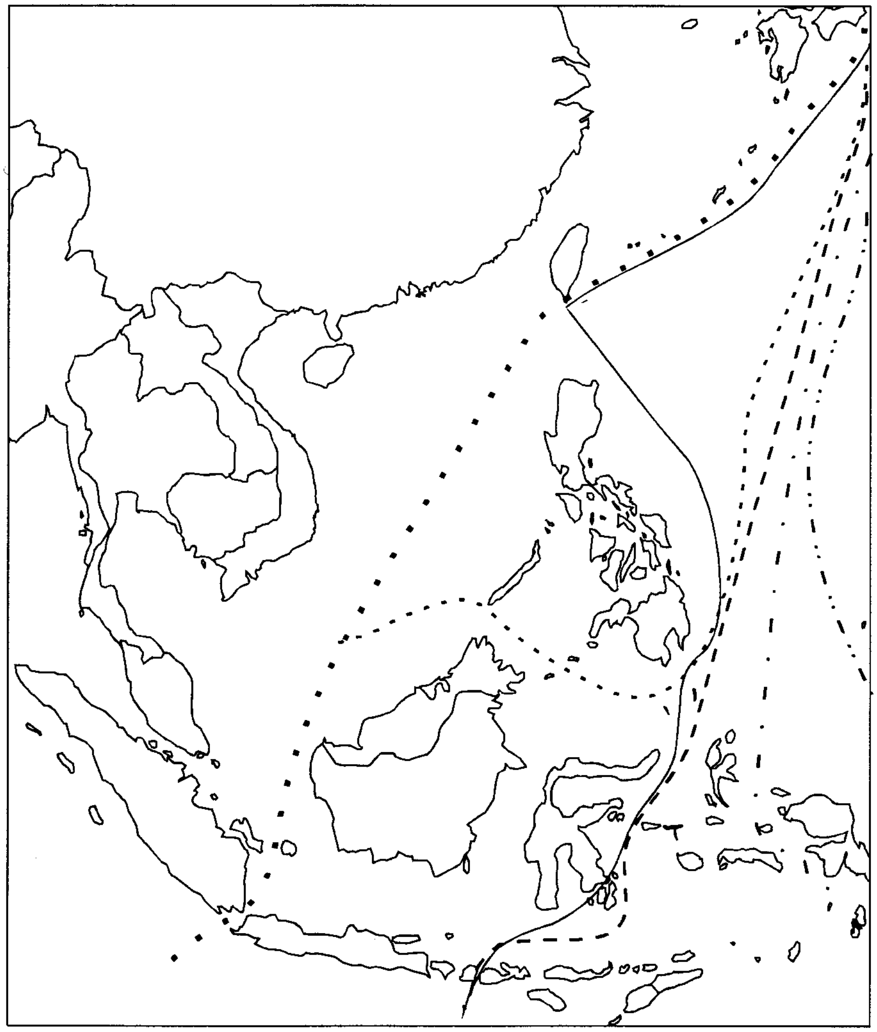

FIG. 1. *The Pacific limits of distribution of grain crops (after Kano 1946 and Chen 1968).* Left to right, Eleusine coracana, Oryza sativa (solid line), Panicum miliaceum, Echinochloa frumentacea, Sorghum bicolor *and* Setaria italica, *and* Coix lachryma-jobi.

sibly for taro. The extraordinary crop diversity of the eastern Solomon Islands (Yen 1973) gives way to a gradual decline in crop varieties across the Pacific into Micronesia and Polynesia (Barrau 1961, Kirch 1982). The inference of many geographers, botanists, and anthropologists (sometimes with reservations [see Chang 1970]) has been that there were two major waves of crop advances out of Southeast Asia: an early dispersal composed of root and tree crops (and sometimes Job's tears) and a later one of grain crops, especially rice (Sauer 1952, Spencer 1963, but see Gorman 1977, Bellwood 1980). Spencer (1963, 1966), for example, characterized early Southeast Asian horticulture as a root-crop complex progressively invaded by grains: "The general trend of events, however, over a long period of time carried the seeded patterns and the grainlike food plants eastward. Rice showed this tendency quite clearly, and it was perhaps the last of the grains to expand at the expense of the tuber-root complex" (1966:117). As (or perhaps even before) the Asian crops moved from west to east, a number of other crops were domesticated in New Guinea or nearby islands. The most important were *Pandanus*, Australimusa bananas, breadfruit, *Canarium*, and probably sugarcane. Three important aroids may have been independently domesticated here: taro, *Cyrtosperma merkusii*, and *Alocasia macrorrhizos*. Crop distributions changed again in the past 500 years with the introduction of American cultigens: sweet potato, maize, manioc, and the taro-like *Xanthosoma*. Sweet potato in particular had a major impact, becoming the dominant crop in highland New Guinea, leeward Hawaii, Easter Island, and New Zealand (Golson 1977, Kirch 1982, Yen 1974*b*). Thus, the observed pattern has been described as having three layers: (1) an early root- and tree-crop horticulture that constituted the universal earliest agriculture, with its greatest elaboration in Melanesia, (2) a partial overlay (but only in the west) of grains, which usually displaced the root and tree crops as staples, and (3) a more general and relatively recent overlay of American crops.

While this view of regional prehistory has been widely accepted, it poses a number of problems (Gorman 1977; Bellwood 1980, 1996; Latinis 2000). One is that there has never been much archaeological support for a taro-yam-sago complex as the earliest Southeast Asian horticulture. (This has usually been assumed to be the result of our limited knowledge of the Southeast Asian Neolithic and the greater difficulty of recovering evidence of root crops than of grains from archaeological sites.) Another is that recent discoveries are pushing the dates for fully domesticated rice back to 8,000 years (Glover and Higham 1996) and perhaps 11,000 years (Normile 1997) in parts of eastern China. While these dates do not eliminate the opportunity for an earlier root-and-tuber Neolithic, they do make it more difficult to assume that there was insufficient time for rice to move farther to the east. This is especially true in light of the history of the sweet potato, which moved quickly over long distances and rapidly became the staple of highland New Guinea. It seems unreasonable to assume that rice and other grains would not have moved farther and faster if they offered comparable advantages.

I will argue that the prehistoric distribution of crops in this part of the world was a product not of differing histories of use in mainland Asia but of the regional patterning of climatic conditions. I provide evidence for an environmental constraint that progressively limits the utility of some kinds of crops as one moves from Southeast Asia into the Pacific: the interannual variability of rainfall. This is not an argument against the relevance of history. Crop distributions reflect the accumulated experience of farmers. Crops that yielded well in a region were maintained; others either never arrived because they did poorly in intervening areas or were not maintained in local cultivation. Where local species could profitably be added to the crop inventories, they were. The unique and varied agricultural systems of the Pacific are ingenious adaptations to local climatic conditions. This argument is not without precedent; both Gorman (1977) and Bellwood (1980) have offered similar suggestions. What is new is the demonstration of an effective constraint.

Climatic Variability in Eastern Asia and the Pacific

Geographical differences in interannual rainfall variability between 30° N and 30° S latitude have been identified in a recent study (Dewar and Wallis 1999) of some 1,500 rainfall stations' records of monthly precipitation between 1940 and the present (Vose et al. 1992). Analysis of Vose et al.'s Global Historical Climatology Network data using an L-moments approach (Hosking and Wallis 1997) produced regions with similar frequency distributions of annual rainfall and described the frequency distribution of each. The measure of variability selected was the ratio of the .10 quantile to the mean annual rainfall, that is, the proportion of the mean rainfall that could be expected in the average driest year in ten. This can also be thought of as a measure of the severity of droughts. We chose to use the .10 quantile rather than a measure such as the coefficient of variation for two reasons. First, rainfall totals are not normally distributed, and therefore the coefficient of variation is a poor measure of spread. More important, it seemed unlikely that particularly wet years caused as many problems as particularly dry ones. (This follows Liebig's Law of the Minimum—organisms' growth is limited by the nutrient in shortest supply.) Because rainfall variability is strongly and inversely correlated with mean total rainfall (Conrad 1941), we used a nonlinear regression to remove the effects of mean total rainfall. The residuals therefore represent the extent to which any region has more or less variability than other regions of similar total rainfall. The residuals were divided into three groups by splitting at the quartiles, yielding three groups: the 25% of stations with high variability, the 25% with low variability, and the middle 50%. A plot of the results (Dewar and Wallis 1999; reprinted in the electronic edition of this issue on the journal's web site) shows that the areas characterized by high variability are often rather small and compact and located along coastlines while the interiors of the continents are generally characterized by moderate or low variability and that many of the areas known to be strongly affected by the El Niño/Southern Oscillation, among them much of the Pacific, Australia, and coastal Peru, are high-variability zones (Ropelewski and Halpert 1987).

Additional rainfall data for regions of anthropological interest in East Asia and the Pacific not represented in the original sample, including the Philippines (15 stations), highland New Guinea (3 stations), the Bismarck and Solomon archipelagos (1 station), and the Atherton Tablelands of the Cape York Peninsula (1 station), were drawn from the Global Historical Climatology Network's beta version 2 (http://cdiac.esd.ornl.gov/ghcn/ghcn.html). Potential stations were examined individually before analysis with the same methods as in Dewar and Wallis (1999) and were retained if they had at least 24 years of complete records that postdated 1940; stations with shorter records, excessive amounts of missing data, or obvious errors were eliminated.

Figure 2 displays the rainfall variability relative to mean annual rainfall for eastern Asia and the Pacific. The most striking feature is the northwest/southeast cline from mainland Southeast Asia to Australia and the western Pacific. Most of Southeast Asia is characterized by relatively predictable annual rainfall, and this becomes less and less the case as one moves to the east. Except for an area of high variability stretching from Hainan to southernmost Taiwan and coastal Luzon and

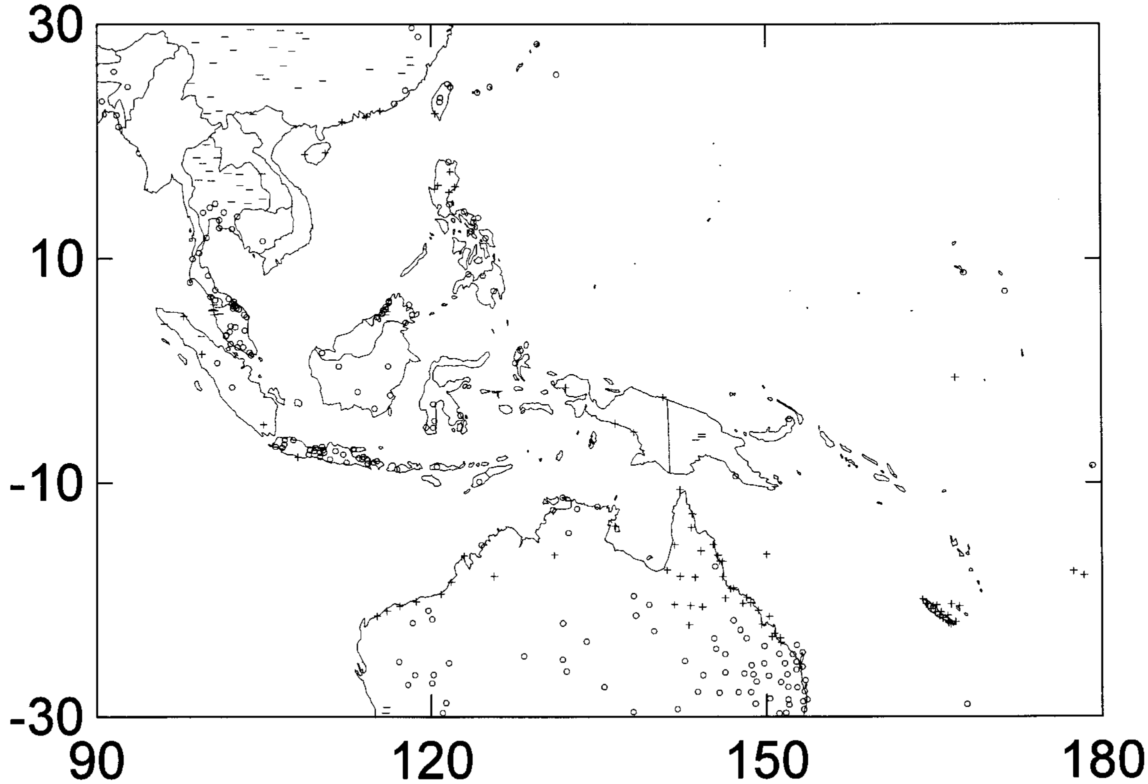

FIG. 2. *Interannual rainfall variability in the Indo-Pacific region, standardized for mean annual totals. +, uncommonly variable; -, uncommonly less variable; ○, near global norms.*

four variable stations on Sumatra and Java, there is a striking increase in variability as one moves into the Pacific. All of the coastal stations on New Guinea except Port Moresby show high variability; significantly, the three stations from the highlands have less variability than one would expect. Most of the northern coastline of Australia shows high variability as well, along with the islands to the east. It is important to keep in mind that this is variability relative to mean annual rainfall. The Central Australian desert has high rainfall variability simply because variability is strongly correlated with aridity. By contrast, the Cape York Peninsula has a wide range of rainfall regimes—for the 26 stations illustrated in figure 3, mean annual rainfall varies between 460 mm and 2,780 mm—but all of these stations except for Herberton Post Office in the Atherton Tableland have high interannual rainfall variability.

Specific comparisons illuminate the magnitude of the differences represented here. The wettest Cape York station is Fitzroy Island, with a mean annual rainfall of 2,780 mm; the Asian mainland site with the most similar annual mean is Goa, with 2,700 mm. Goa is in a region of average variability. Figure 4 presents histograms of 20 complete years of records for Fitzroy Island and Goa. It is evident that the hypervariable Cape York station has a much less compact distribution; not only are the dry years drier than in Goa but also there are far fewer years with nearly normal rainfall. At the other end of the rainfall spectrum on Cape York is Julia Creek, with a mean annual rainfall of 462 mm ($n = 28$). Few parts of tropical Asia are as dry. Xigaze, in Tibet, comes closest at 429 mm ($n = 28$). Once again, the Cape York distribution is broader and less tightly clustered around the mean. Finally, the annual rainfall data for Herberton Post Office ($n = 48$, mean rainfall 1,188 m) contrast with those for Guiyang, Guizhou, China ($n = 49$, mean rainfall 1,159 mm). Herberton is the only station in the Cape York sample with rainfall variability within the median 50% of global stations, but its distribution is still markedly broader than at Guiyang, which is located in a region of less variable rainfall.

One of the more important contributors to rainfall variability worldwide is the El Niño/Southern Oscillation, and this is known to have varied in patterning and importance over the past century and a half (Urban, Cole, and Overpeck 2000). Proxy records of various kinds have detected changes in the importance of the El Niño/Southern Oscillation in the course of the Holocene (e.g., Sandweiss et al. 1996, Haberle and Ledru 2001, Haug et al. 2001), with an apparent intensification commencing about 5,000 years ago. A recent analysis of annually banded corals from New Guinea has shown that the El

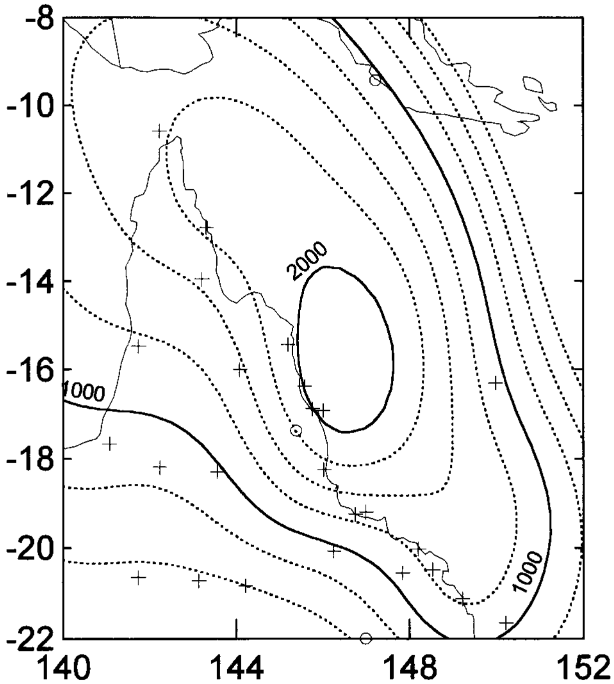

FIG. 3. *Interannual rainfall variability in the Cape York Peninsula and isohyets of mean annual rainfall (mm). +, uncommonly variable; ○, near global norms.*

Niño/Southern Oscillation has existed, in varying strength and patterning, for 130,000 years (Tudhope et al. 2001, Cole 2001). It is not, however, the only cause of interannual rainfall variability. Comparison of 16 macroregions of high interannual rainfall variability (Dewar and Wallis 1999) with Ropelewski and Halpert's (1987) mapping of the global effects of the El Niño/Southern Oscillation on precipitation patterns revealed that the majority of the high-variability macroregions were not subject to any marked El Niño/Southern Oscillation effect. Not surprisingly, a strong link to the El Niño/Southern Oscillation was evident in New Guinea, parts of Australia, and New Caledonia. In other areas of high variability, other geophysical processes must be playing a role. One globally consistent feature of high-variability areas was their tendency to be located on islands or along coasts. Thus, it seems likely that the dynamics of the Atlantic and Indian Oceans are also important in determining the modern geographical patterning of interannual rainfall variability. In addition, it is very likely that substantial changes in the configuration of landmasses such as occurred during the glacial maxima would have strong effects on local climatic patterns.

Responses to Interannual Rainfall Variability

Interannual variation in rainfall poses problems for farmers and foragers alike, and when variability is great it is a significant constraint. The first response to a resource shortfall will be an expansion of the diet to include resources not normally consumed, often called famine foods. Several additional responses have been proposed for foragers in temporally variable environments (see Cashdan 1992): (1) They may spread the risk either by sharing or by moving to nearby regions where climatic conditions are more nearly normal. This strategy is best suited to regions where resource shortages are local. (2) They may shift their attention to resources that are less variable, perhaps by adjusting their settlement shifts and resources exploitation schedules. This usually will result in a decline in foraging efficiency but a reduced risk of crisis. (3) They may store food to deal with future crises.

In areas where rainfall variation is correlated over wide areas, the first option will be of limited utility. Storage works well for short-term shortages, but few foragers are able to store enough to weather major droughts. The second option is probably the most important. There are two classes of resources that will usually offer reduced variability: (1) those that produce and store energy over many years and thus can be harvested even in very difficult years and (2) those whose productivity is unaffected by short-term rainfall declines (Latinis 2000). The most common form of the first type is long-lived perennial species of plants with specialized storage organs. In the western Pacific, a typical example is the sago palm (*Metroxylon* spp.); the energy available in its pith derives from 8 to 15 years of growth. In contrast to those of annual plants, many fruit producers, and the animal species that depend upon them, these perennials' yields will not decline quickly with prolonged drought. The second class of variation-reducing resources consists of those that are unaffected by rainfall, and the most important of these are aquatic resources, whose food chains are not directly tied to terrestrial productivity.

For farmers, a similar range of options is available. In general, their ability to move away from the drought will be more limited than that of foragers, although some members of a family may move to stay for a while with distant friends and family. Storage is more likely to be important than among foragers. It should be noted, though, that most farmers store to feed their families from one harvest to the next; storage specifically established to deal with critically poor harvests is less common. In some circumstances, trade may function to spread temporal risk (Cashdan 1992). Farmers can also choose to plant varieties and species whose yields are less sensitive to rain shortfalls. As in the case of wild resources, there may often be a trade-off—more secure resources may be more expensive to process, have lower yields in good years, or be less palatable. Where feasible, they can establish irrigation systems to replace rain with surface water. The least secure crops will be those whose yield is strongly dependent on adequate and punctual rainfall. In areas where rainfall is highly variable, a reliance on such crops means that famine will frequently follow droughts. Crops that are planted to mature simultaneously exacerbate this problem, since an entire field's yield will depend on the timely arrival of rain.

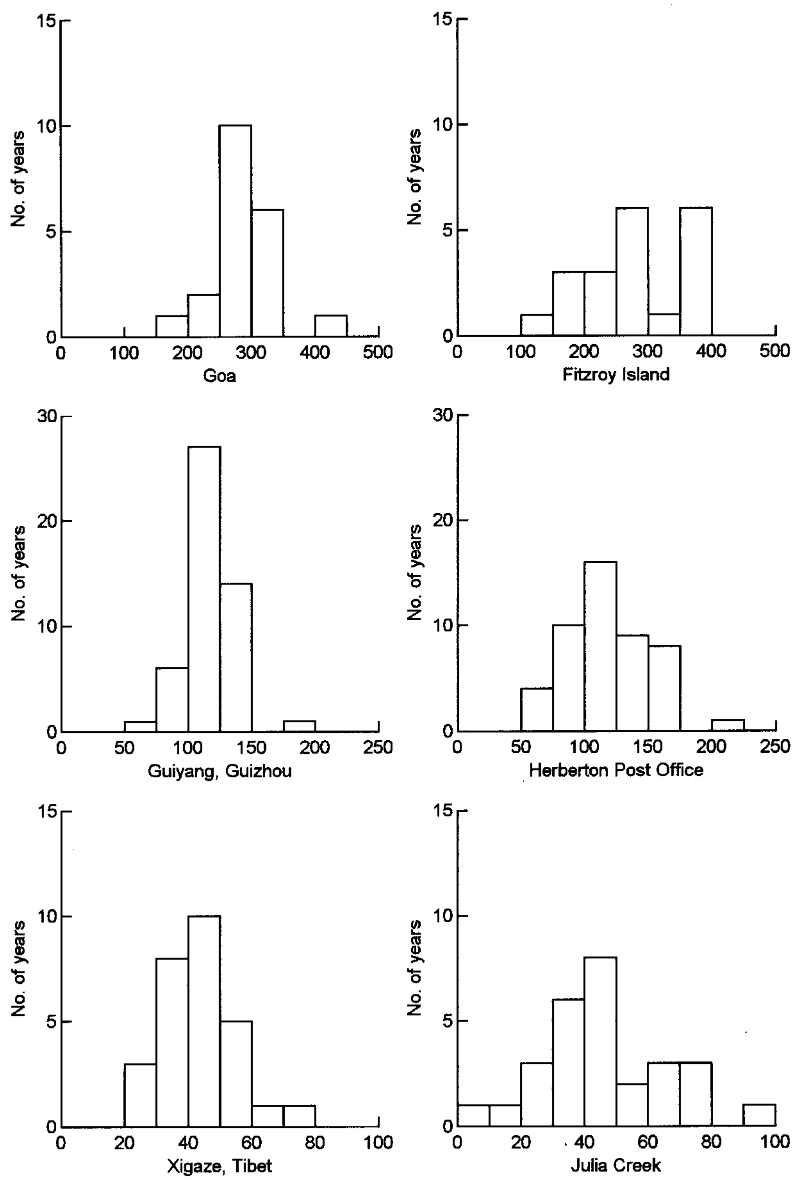

FIG. 4. *Frequency distributions of annual rainfall total (cm) in three stations of the Cape York Peninsula (*right*) compared with three Asian stations of nearly matching rainfall totals (*left*).*

Conversely, crops or planting regimes that are less strongly dependent upon rainfall timing and amounts will offer more security, and so will perennial crops that slowly store energy and average across years.

The Rainfall Variability Constraint

Jacques Barrau (1965) drew attention to a major division in the environments of Indonesia and the western Pacific between rain-forest zones ("the wet") and savanna/woodland zones ("the dry"). His illustration of these zones has an equatorial band of wet oriented east-west with drier zones to the north and south. The patterns of interannual rainfall variability described above suggest that another environmental gradient, with the contrasts running from west to east, overlies Barrau's zones. My argument is that the increasing variability of annual rainfall as one moves from the Southeast Asian mainland through New Guinea and into the Pacific served as a progressively restrictive environmental constraint, leading farmers to avoid planting crops with unreliable yields and to exploit resources less affected by rainfall disturbances.

Grains, as annual plants that mature simultaneously in a field, are likely to be relatively high-risk crops. The distinct distributions of grains across island Southeast

Asia correspond well to expectations. The most limited grain is finger millet (*Eleusine coracana*), of which Purseglove notes: "It requires a well-distributed rainfall during the growing season with an absence of prolonged droughts. In drier areas with unreliable rainfall sorghum and bulrush millet are better suited than finger millet" (1972:149). What limits common millet (*Panicum miliaceum*) is less clear, but Burkill saw little economic prospect in it, nothing that "it has been grown experimentally in Java and in the Malay peninsula . . . but the chance of dry weather at harvest is not sufficiently assured" (1966:1686). Burkill described rice, *Oryza sativa*, as particularly sensitive to water, particularly hill rice: "Though it is customary to speak of dry-land rices it must be remembered that they require a humid atmosphere and endure no desiccation. As a result of their demand for moisture, the area of the whole world in which dry-rice cultivation is practiced is limited. They demand an assured rainfall over 3 to 4 months, and this greatly limits their cultivation" (p. 1623). Japanese barnyard millet (*Echinochloa frumentacea*) has a broader distribution and may be less sensitive to water shortages; Purseglove notes that it is the fastest-growing grain and that in China and Japan it is "grown as a substitute for rice when the paddy fails" (1972:145). Sorghum (*Sorghum bicolor*), as Purseglove notes, "because of its drought resistance, is the crop *par excellence* for dry regions and areas of unreliable rainfall" (p. 262), though Burkill reports that in a two-year trial in Malaysia it only once had good yields. Foxtail millet (*Setaria italica*) is another crop of arid zones, but Purseglove reports (p. 257) that "it is susceptible to long periods of droughts." Job's tears (*Coix lachryma-jobi*), though nowhere a staple or a very important crop, has the broadest distribution of all. Burkill reports that it is grown in "remote parts" and requires less water than dry-land rice. Barrau (1958:49) reports that in Melanesia it was used only as an ornamental, except perhaps occasionally in New Guinea. Overall, there is a consistent pattern: the grains with the broadest distribution are the least susceptible to drought.

The two most important Asian-origin staples, taro (*Colocasia esculenta*) and yams (*Dioscorea*), were the hallmarks of Barrau's division between the wet and the dry. In wet fields, taro grows nearly continuously and can often be harvested throughout the year. As Barrau notes, "*Colocasia* grown without irrigation is always found in natural surroundings which provide sufficient humidity, such as the rain forest" (1958:41). The frequent association of irrigation with taro production is ascribed by Spriggs (1990) partly to the greater environmental control that irrigation offers. Wild species of *Dioscorea* are pantropical and are often found in seasonally arid climates. Indeed, the yams' perennial habit, sending up a vine when the rains come, makes them capable of tolerating water stress. Both wild and cultivated forms must retain their starch and water until growth can recommence. Hather (1996) argues, however, that many *Dioscorea* species have their origin in the humid Tropics and that their reliance on vegetative reproduction is not simply an adaptation to seasonally drier conditions.

Of the plants that were brought into cultivation in eastern Indonesia and Melanesia (see Yen 1982, Golson 1989, Latinis 2000), the most important are the tree crops sago palm, *Pandanus*, and breadfruit, the rather treelike bananas of the section Australimusa, sugarcane (*Saccharum officinale*), and the giant aroids *Cyrtosperma merkusii* and *Alocasia macrorrhizos*. All of these are crops whose growth to harvest takes longer (sometimes much longer) than a year. None of the staples of certain New Guinea origin are annuals. Many of these crops (e.g., *Pandanus*, breadfruit, and *Cyrtosperma*) had centers of diversity and economic importance farther east. Others had wild relatives far beyond their zones of economic importance (e.g., sago palm and *Cyrtosperma*).

In an uncertain environment, one advantage of tree crops may be the high certainty of return on the initial investment of planting: tree crops will yield over many years, even if not every year. Another may be that investing in a wide variety of species spreads risk. Different species yield at different times of the year and are affected differently by any single year's vagaries of climate.

To summarize, the progressively more variable annual rains reduce the attractiveness of reliance on some annuals, especially grains, and make more attractive species that store starch over many years, grow continuously so that fields are harvestable at several points in the year, are relatively drought-resistant, or repay investments over many years.

Increasing rainfall variability may be important, for example, in determining the boundary between "horticultural" New Guinea and "hunting and gathering" Australia along the Torres Strait (Harris 1977, 1979, 1995; Yen 1995). The Australian landscape has been manipulated by aboriginal peoples for a very long time, with the productivity of some important wild food resources being intentionally enhanced or maintained by various methods, in particular the controlled use of fire (Latz 1995). Yet it is clear that aboriginal Australians domesticated no crops and planted no gardens.

Harris (1977) has shown that there was a continuum of subsistence from the New Guinea coast to Australia through the island groups that lay between. On the south coast of New Guinea, limited horticulture was practiced by peoples who were primarily dependent upon sago palms, both wild and planted (Ohtsuka 1977, Harris 1995). As one moved across the strait, horticulture became less and less important until it finally disappeared, while a focus on marine resources became ever more important. The human communities across the strait were not isolated from one another but linked by trade (Harris 1979) and a limited amount of intermarriage (Macknight 1980, Kirk 1973). Yen (1995), reviewing the distribution of cultivated and wild species of economic importance in Australia and New Guinea, has found that both taro and the greater yam *Dioscorea alata* are now known as wild species in Australia. How long these species have been in Australia is unknown, though Yen notes that Telford (1996) has identified *D. alata* as a recent introduction. Telford has also noted two other naturalized species of *Dioscorea* in Australia, *D. bulbifera* ("perhaps of extra-Australian provenance") and *D. pentaphylla* ("perhaps of pre-European introduction") (pp. 198–99).

Many explanations for the absence of agriculture in Australia have been suggested (Golson 1971, Frankel 1995, Gosden 1995, Yen 1995), but I believe that the environmental constraint of increased unpredictability of rainfall is close to the heart of the matter. It can be regarded as a substantiation of Flannery's (1994) and Diamond's (1998) suggestion that the tropical Australian climate and soils are ill-suited to agriculture. Both sides of the Torres Strait have highly variable rainfall regimes. As many have pointed out, the south New Guinea coast is, at best, only a marginal area of agriculture. Most of the groups there are hunters and foragers, with a very high reliance on sago palm. Ohtsuka (1977) shows that the groups he studied got much poorer yields of calories for labor in their gardens than from sago collection, and indeed they obtained 75% of their plant-food calories from sago. Yet he also noted that population density in the region was very low. It is tempting to argue that these groups are essentially limited by the availability of sago, which does not grow south of the Torres Strait.

Moving from island to island across the strait, there is a progressive reduction in reliance on agriculture, and Harris (1977) notes that agriculture was historically more important on the smallest and ecologically least productive islands. One way of understanding this may be that the uncertain yields of agricultural fields were tolerated only where there were few alternatives. At the same time, the more southerly populations paid increased attention to marine resources, the kinds of resources least affected by variation in rainfall.

In the hypervariable Cape York region, agriculture is subject to a high risk of failure. Europeans in Australia have had little success in establishing viable agriculture in any part of northern Australia except the Atherton Tablelands (Jones and Bowler 1980), where the one station examined has less interannual rainfall variability than any of the others from Cape York. The distribution of the apparently introduced taro and yams is also of some interest. *Dioscorea bulbifera* is found only along the northern coastline of Australia, including Cape York; *D. pentaphylla* is limited to Thursday Island, near the southern limit of historically attested agriculture (Harris 1977); *D. alata* is confined to a small area of the coastal Northern Territory and the Cape York Peninsula. In contrast, the two native species of *Dioscorea* identified by Telford (1996) have very different distributions: one is widespread in coastal forests from the northwestern Kimberley region to New South Wales, and the other is limited to southwestern Western Australia. As mapped by Yen (1995), *Colocasia esculenta* is found largely along the northern coast, although it extends south along the coast to northern New South Wales. One can only speculate as to how and when these plants were introduced, but it is possible that they are relicts of attempts to establish agriculture in northern Australia. In fact, there is evidence of a period in the mid-Holocene when the El Niño/Southern Oscillation was less potent (Keefer et al. 1998, Sandweiss et al. 1996, Haberle and Ledru 2001). Since the rainfall variability in the Cape York area is closely linked to this phenomenon, the region may once have been more forgiving for agriculture.

In the rather distinctive agricultural system of Botel Tobago, documented by Kano and Segawa (1945), in contrast to that of most Taiwan aborigines, rice was not grown at all and millet, though ritually important, was a secondary crop. The staples were taro, yams, and sweet potatoes. Taro was cultivated in irrigated pond fields as well as in dry fields. This is unusual for two reasons: irrigated pond fields were not in use anywhere else on Taiwan until the arrival of Chinese immigrants (Chen 1968), and the use of pond fields exclusively for taro is very rare outside of the Pacific. Taro was harvested on a daily basis throughout the year, and as each plant was dug the upper portion of the corm and the attached leaves were replanted in the same location. Kano and Segawa (1945:117) comment that a plant requires two or three years to be harvestable and note that, given this poor yield, "swamp taro is not so good a crop as the Yami think it is."

The rainfall stations of Taiwan are all of average variability except for Kao Hsiung, the station on the southwest coast closest to Botel Tobago. Kao Hsiung receives a mean rainfall of 16,800 mm, but in the driest year in ten only 57% of that mean falls. Stretching west and south is a zone of high variability of which Botel Tobago seems to be a part. The reliance on irrigated taro is probably best seen as an adaptation to a climate of extremes. Taro is available year-round but at a high cost for the construction of the fields and at relatively low rates of production. In contrast to the case of irrigated taro fields in New Caledonia (Spriggs 1982*a*), political stratification plays no role in explaining agricultural intensity on Botel Tobago; Kano and Segawa (1945:2) note that the Yami "have had no headman or chief."

Eastern Melanesia is a region of very high rainfall variability, and many of the special features that Yen (1973: 82–83) outlines are probably adaptations to that variability. First, it is characterized by an unusual degree of reliance upon plants that average across years by storing starch, it is the easternmost region in which sago is cultivated, the aroid *Alocasia* is more than just an emergency food, and it is the southernmost region in which the giant aroid *Cyrtosperma* is important. Second, this region saw an unusual development of storage techniques. It is the westernmost region in which semi-anaerobic fermentation of breadfruit was employed (see Kirch 1982) and the only region in which breadfruit was preserved by drying. Third, many of the Southeast Asian tree crops underwent extensive selection and development into cultigens here. Finally, and in a parallel to Botel Tobago, it is the westernmost Pacific region with complex irrigation pond fields for taro. Kirch (1982) drew attention to the ways in which Polynesian agronomic systems seemed designed to withstand stochastic hazards such as drought, cyclones, and floods. Eastern Melanesia, with a somewhat larger suite of crops, seems equally attuned to such problems, and this seems likely to be because it, too, is an area of great climatic variability.

Implications for Prehistory

Recognition of increasing rainfall variability from Southeast Asia into the Pacific as an important environmental constraint requires us to rethink the role of modern or historic geographical distributions of crops in reconstructing crop or agricultural history. It seems very unlikely that rice has a more limited distribution in insular Southeast Asia than foxtail millet because it was domesticated later. In fact, current evidence suggests that rice was domesticated no later than foxtail millet and in a region far closer to insular Southeast Asia. Similarly, the broader spread of taro and yams relative to rice need not indicate a historical priority of root and tuber cultivation over grain cultivation in Southeast Asia. Taro and yams may have been cultivated earlier than rice in mainland Southeast Asia, but that is a problem to be resolved with archaeological data rather than with modern distributions.

If, as many have proposed, migrants from Southeast Asia carried taro and yams to New Guinea and Melanesia, there is no need to infer that they came from a homeland that did not grow grain. Indeed, several terms for "rice" have been reconstructed for Proto-Austronesian, the ancestor to the languages of Oceania (Blust 1988). Bellwood (1980), following Spencer (1963), proposed that latitudinal changes in photoperiod operated as a filter that limited the initial spread of rice. Others have found Bellwood's filter an unlikely one (Spriggs 1982*b*), and, as Bellwood noted, it does not explain the cases of the other grains.

Over the past several years there has been growing acceptance of an early start for agriculture in New Guinea, based on Golson's work at Kuk (1977, 1989; Yen 1982, 1995). At the same time, it has not been clear whether early agriculture in Melanesia was an independent development based upon indigenous crops or started with the diffusion of Southeast Asian crops, to which local crops were added. Either model is consistent with the distributional evidence; the decisive data will come, once again, from archaeological evidence of the ancient crop inventories. For example, Kirch's (1989) archaeological research in the Mussau Islands of Melanesia firmly established reliance on a suite of tree crops in the 2d millennium B.C. The increasing variability of rainfall of Melanesia in comparison with areas to the west does mean, however, that Southeast Asian agricultural systems could not have been transferred without modification.

Conclusions

In the western Pacific, rainfall variability and the prospect of drought are increasingly serious environmental challenges as one moves from west to east. The interior of Southeast Asia has relatively low variability in rainfall totals from year to year, when standardized against the mean. As one moves to the east, the impact of the El Niño/Southern Oscillation becomes stronger and very dry years become more common. The result is an increasingly stringent environmental constraint on certain forms of agriculture.

The increasing risk of severe shortfall of rain is the likely reason that the grain crops of Asia did not spread to New Guinea or into the Pacific. It is now very difficult to argue that their spread into island Southeast Asia came too late in prehistory; they were domesticated early in the Holocene, and they are in many cases very widely distributed across Asia to the west. Their eastern border is analogous to the geographical limits of pre-Columbian maize cultivation in North America. Maize was grown only in areas where the growing season was usually long enough to permit a harvest (Riley, Moffett, and Freimuth 1980). Where the grains and other annuals proved too likely to fail, farmers focused their attention on roots and tubers, tree crops, crops grown in swamps, and, in a few areas, taro grown in irrigated fields. In areas extremely prone to drought such as eastern Melanesia and the tropical Pacific, elaborate forms of long-term storage were developed. In Botel Tobago farmers grew no rice and relied upon taro from irrigated fields as a staple, even in the face of fairly poor yields.

Finally, it seems likely that the extreme variability of rainfall made the cultivation of crops in fields an unattractive import across the Torres Strait. Cape York is largely a place of agricultural failure today and must have been so in the past during periods with climatic patterns similar to today's. It is worth noting that the climatic conditions on the north side of the strait were not much different from those on the south and that the peoples of the south coast of Papua New Guinea were not very dependent upon horticulture.

My argument here is fundamentally a historical one. Faced with unpredictable rainfall, people sought viable economic strategies and abandoned unsuitable ones. The crops that farmers tried out in their fields were domesticated and transported by people. Beyond the limits of acceptable reliability and utility, crops were dropped from farmers' repertoires. The ways of life of the peoples of the western Pacific are reflections of human ingenuity and history in the face of unusual challenges.

Comments

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An interesting environmental correlation notwithstanding, Dewar's argument turns on its head almost everything I thought I knew about traditional agriculture. I have always considered root and tree crops as the cultigens of choice in the Tropics primarily because they tend to require low labor inputs but also because they tend to be resistant to diseases, many do well in poor soils or rugged terrain, many allow for planting and harvest to be carried on throughout the year on an as-needed basis, and in general they are not subject to relatively short-term variations in rainfall. Because of these advantages, in tropical areas one would expect tree and root crops to have been brought under domestication first. According to Piperno and Pearsall (1998), there is good evidence that this was the case for the tropical Americas. Despite the discovery of early rice in China, as noted by Dewar, it may still be the case that tuber and tree crops preceded rice and other seed crops in tropical island Southeast Asia, though firm evidence is still lacking one way or the other.

Empirically, root and tree crops were traditionally exclusively grown throughout the far-flung islands of the tropical and subtropical Pacific. However, I am not at all certain that the ultimate cause of this pattern is high interannual rainfall variation. The eastern Micronesian islands of Pohnpei and Kosrae have very high annual rainfall totals (about 5,000 mm), seasonality of rainfall is minimal, cyclonic storms are rare, and year-to-year variation tends to be small and basically irrelevant for plant growth given the surfeit of rain.

As for the reason people on Pohnpei and Kosrae traditionally depended on root and tree crops, it is not unlikely that a strong element of history enters into the picture. Perhaps the original settlers arrived with only root and tree cultivars 2,000 years ago (Athens, Ward, and Murakami 1996). One does not, however, have to live long on Pohnpei and Kosrae to appreciate the real advantage of growing and depending on root and tree crops. Given the extensive cropping systems prevalent on these islands, only a small amount of labor is required for their production. The reason people do not grow rice or some other seed crop is entirely labor-driven, and this would be true anywhere in the tropical Pacific (though obviously some locations require significantly more labor effort to secure certain kinds of root crop production—e.g., Hawai'i, with its large irrigation and taro pondfield systems [Earle 1978]).

Turning to the opposite side of the equation, I keep wondering why the Ifugao and Bontok Igorot of northern Luzon in the Philippines grow rice. Luzon, after all, is on the margin of the area of the western Pacific that is most intensively affected by El Niño–caused droughts (Ropelewski 1992). The reason must be that rice is much more efficient than taro and other root and tree crops in terms of land use and given the relatively high population densities of the region. Certainly the level of agricultural intensification that is evident—elaborate terrace and irrigation systems—suggests a considerable need for land-use efficiency. Seed crops tend to be favored under conditions of high population density when land-use efficiency is at a premium. They often require very high labor inputs to secure and/or maximize their production (what I call "energy subsidies" [Athens 1977]), but caloric yields tend to be relatively high per unit area compared with those of tuber and tree crops. It is for this reason that maize is planted at lower elevations in the northern Andean valleys and potatoes are largely relegated to the higher areas on valley slopes (see Knapp 1984, Knapp and Denevan 1985). Thus, unless forced by either highly seasonal rainfall/water availability (or temperature) and/or high population densities, I do not expect to see people growing seed crops in the Tropics as dietary staples.

The correlation documented by Dewar, if real, may be unrelated to causation. Causation in the development and use of agricultural systems is a complex subject, and certainly with respect to traditional Pacific island agriculture one should not discount the role of history in explaining why intensified production systems, where they are present, developed around root and tree crops rather than seed crops. Apart from historical factors, labor effort and population density appear to be powerful determinants in the selection of these crops.

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16 I 03

The devastating drought of 1997–98 destroyed vast areas of tropical rain forest and displaced thousands of people from marginal agricultural lands in the islands of New Guinea and eastern Indonesia. This event served to heightened our awareness of both the long-term vulnerability and the potential resilience of food production systems in a region of high El Niño–related climate variability. Dewar's insightful analysis of the constraints that interannual climatic variability can place on subsistence provides us with a significant data set with which to investigate the driving forces behind the evolution of sustainable agricultural production at a regional scale. While he presents us with a convincing argument that climatic variability is a fundamental determinant of the distribution of subsistence systems in the ethnographic present, there is a deeper time dimension that warrants consideration here.

One of the most significant outcomes of recent paleoclimatic research in the region is that climate variability itself is dynamic from interannual to millennial time scales (Chappell 2001, Haberle, Hope, and van der Kaars 2001, Tudhope et al. 2000). In other words, the frequency, duration, and intensity of severe climate events such as the drought experienced in 1997–98 have shifted continuously through time. Shifts in climate variability have been shown to have had profound consequences in prehistory. Archaeological evidence points to the early Holocene as the period of agricultural origins, including the development of the rice-based agriculture of Southeast Asia and the tuber-based agriculture of the highlands of New Guinea (Bellwood 1996). In the context of Dewar's argument, the decision to adopt grains, tubers, or tree crops appears to have been made during a period of great climatic stability, between 9,000 and 5,000 years B.P., when the intensity and frequency of drought events in the islands of eastern Indonesia and New Guinea were significantly subdued relative to those of today. It is not until after about 5,000 years B.P. that El Niño–related drought events similar in intensity and frequency to those of today are registered in the paleo-records.

What does this mean for the argument that increasing climate variability towards the western Pacific and Australia was a major constraint on the type of crops grown and even the choice to grow crops? It is possible that the rate of spread of cultigens beyond their area of origin in the early Holocene was too slow and was eventually thwarted by the onset of increasing climate variability by 5,000 years B.P. This seems unlikely given that (1) crops such as rice had at least 4,000 years to move eastward from their centre of origin in eastern China to Southeast Asia and New Guinea and (2) rice has been rapidly incorporated into traditional subsistence systems in regions of high climate variability such as New Guinea. The spread and adoption of new crops are more likely to be a function of a complex set of constraints that include environmental as well as social factors. It is clear that to sustain tuber crop production after 5,000 years B.P. in the highlands of New Guinea continued innovation and adaptation were necessary. The development of grid patterns of field ditches for greater ground-water control and the integration of agro-forestry techniques to enhance soil fertility in dryland fallow systems both occurred between 2,000 and 1,200 years ago and appear to be a consequence of chronic drought stress in the region at that time (Haberle and Chepstow-Lusty 2000). These correlations in prehistory imply that a shift in climate variability is not simply background information of little relevance to cultural change but must be considered as part of a continually changing set of problems and opportunities that alter the context for subsistence.

Finally, the climatic explanation for the maintenance of a divide between the hunter-gatherers of Australia and the agriculturalists to the north appears to be gaining support (Chappell 2001), though I believe it remains problematic. While the Torres Strait represents the shortest distance between the agriculturalists of New Guinea and the hunter-gatherers of the Australian mainland, this is by no means the only avenue open for dispersal of domesticated plants into Australia. In central northern Australia, where Dewar's measure of climate variability is comparable to that of the cereal-based regions of Southeast Asia, there has been considerable opportunity for exchange of domesticated plant resources (e.g., coconut) through contact with either Melanesians and Macassans or through natural dispersal. There remained a resistance to integrating plant resources into existing subsistence systems on mainland Australia that cannot be solely related to climate variability but must incorporate a range of factors including environmental (unpredictable climate, poor soils, high fire risk) and social factors. The climate data set presented by Dewar will provide a much-needed springboard for wider analysis of the role of environmental and social constraints on food production.

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By focusing on the environmental factor of interannual rainfall variability, Dewar has made an important contribution to the continuing debate on the agricultural prehistory of Southeast Asia and the Western Pacific. Inherent in his hypothesis is the assumption that, were it not for the limiting factor of interannual rainfall variability, agricultural subsistence systems would have spread further in the region than they did. This may well be true in some situations—notably the west-to-east filtering out through island Southeast Asia of rice as a staple crop—but it overlooks inherent differences in the "expansion capacity" of early agricultural systems (Harris 2003).

Dewar argues convincingly that interannual rainfall variability exerts a strong influence on the subsistence options of foragers and farmers, but he does not sufficiently consider the contrast, in the Southeast Asian and Pacific context, between the root- and tree-crop systems, which are non-expansive, and the systems based on the annual cultivation of grain crops, which have a built-in tendency to expand. Because the staples of the former systems are roots, tubers, and tree crops, most of which yield mainly carbohydrate and do not alone provide a nutritionally balanced diet, they need to be complemented by protein and lipids obtained from wild resources (fish and game animals) and, in some parts of the region, from domesticated animals (chickens, pigs, cattle). They tend not to expand into new environments and remain embedded in their local territories, responding to increased demand by intensification of production rather than by territorial expansion. Grain-based systems, in contrast, provide plentiful vegetable protein as well as carbohydrate (and sometimes also vegetable oils), and this more nutritionally balanced food supply favors territorial expansion by freeing grain farmers, who often also raise domestic livestock, from continuing dependence on local wild resources.

I have suggested (Harris 1995) that this contrast helps to explain why the system of root- and tree-crop cultivation in New Guinea, which is at least 6,000 years and possibly 9,000 years old in the highlands (Golson 1989), did not spread south across Torres Strait into Australia. Dewar is right to point out that the high interannual rainfall variability that characterizes much of northern Australia could have inhibited the spread of agriculture from southern coastal New Guinea across Torres Strait and down the Cape York Peninsula because crop yields would have become increasingly uncertain along that north-south gradient. This, however, begs the question why people who could obtain a well-balanced diet by hunting, fishing, and gathering plant foods (including starch-rich sago north of Torres Strait) would have adopted the riskier and more labor-intensive strategy of crop cultivation.

There is evidence, in the form of relict mounds and ditches on several islands in Torres Strait, of some former small-scale cultivation, but this does not imply that agriculture was a basic and widespread subsistence activity. Indeed, I have proposed that crops may have been cultivated on a small scale because they provided islanders with exchange goods that enabled them to participate in the extensive trade network that linked the islands and spanned the strait in the 19th century (Harris 1979). However, this hypothesis remains tentative in the absence of adequate archaeological evidence for the antiquity of the relict fields and the time depth of the historically documented pattern of trade.

Despite my scepticism about the likelihood of root- and tree-crop cultivation's ever having spread into Australia across Torres Strait, I welcome Dewar's suggestion that the presence in parts of coastal Northern Territory and the Cape York peninsula of taro and two species of yam thought not to be native to Australia may testify to former (mid-Holocene?) attempts to "establish agricultural fields" there. Perhaps archaeological testimony in support of this speculation will one day be found, but meanwhile we must remember that no evidence in the form of relict fields or the remains of cultivars has so far been discovered anywhere in northern Australia.

Dewar has done students of early agriculture in the Tropics a signal service by raising our awareness of the potential importance of interannual rainfall variability as a factor that can help to explain spatial and perhaps temporal variations in the patterning of agricultural systems. He makes a strong case for its relevance to the (pre)history of Southeast Asian and Pacific agriculture, and it is to be hoped that he will now undertake comparable studies in other regions of the world where there is a history of interaction between grain-based and root- and tree-crop-based systems, such as West Africa and parts of Central and South America.

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Dewar's intriguing thesis is a significant step toward increased understanding of subsistence system evolution and diversification. The methodology has global application and will benefit researchers in other regions. Archaeologists have more than occasionally used potentially misleading averages (e.g., annual mean rainfall) as measures for assessing resource availability/distribution, risk, response, resistance, and so forth. Dewar demonstrates that rainfall variability over long periods may be a better measure for assessing regional and interregional differences.

It also appears that he is not intent on invalidating Barrau's north-south (wet/dry) isoclines. Instead, he augments Barrau's and others' ideas, forcing researchers to rethink subsistence development models and the factors those models are based on.

Research in eastern Indonesia has taught me that hammering observed subsistence practices into traditional models may be inappropriate. I caution Dewar and others that there may be other subsistence economies which may belong to undetermined "core" economies, somewhat like single categories inclusive of all variation (Latinis 1999), but distinguishing between variability within a core and variability across cores is difficult. Are palm-based economies in Malaysia, Nias, Maluku, and Melanesia homologous or analogous? Do root-crop economies with arboricultural supplements belong in a separate core from arboreal-based economies with a root-crop supplement?

I am not satisfied with the traditional categories "forager" (hunter-gatherer)," "horticulturalist," "agriculturalist," etc. Some general trends are fairly clear (e.g., farming to horticulture/arboriculture to foraging from mainland Southeast Asia to Australia), but I wonder whether specific core subsistence categories at a more fine-grained analytical level in case-study areas such as the Torres Straits have been properly identified/classified.

Another issue is the presence of agriculture in some areas where Dewar suggests it should not be. His "small-island constraints resulting in a need for 'risky' agriculture" is worth further exploration, but larger islands such as Halmahera in eastern Indonesia have produced rice. Eman Bowen's colonial map (in the Singapore Heritage Conservation Center) states that Gilolo (Halmahera) "produced great quantities of rice and sagu." Other examples can be found in the Pacific and elsewhere. Additionally, transmigrant wet-rice farming has taken hold in eastern Indonesia. Also, many Malukan oral traditions have a rice origin myth, and some upland groups occasionally plant swidden rice. What about interior areas with less rainfall variability?

Few Malukans and only those adjacent to transmigrant villages have, however, adopted wet-rice farming. During recent ethnographic work (1992–98) I found transmigrant farmers complaining of decreased yields over several decades and a need to expand new paddies or use more fertilizers and pesticides. Moreover, there is no firm archaeological evidence for a past predominance of agriculture or the existence of any significant grain-based agricultural strategy at all. Perhaps wet-rice farming and grain agriculture are unsustainable and risky. Unquestionably, Malukans and even Halmaherans rely predominantly on arboreal-based economies enhanced with root crops and marine resources. Thus, exceptions do not necessarily negate Dewar's insights.

I question whether rainfall variability is the major or even the only important variable. East/northeast west/southwest isoclines have been noted as far back as Wallace (1869). Do established flora and fauna contribute to resistance to agriculture? What about technology, raw material, cultural preference, geology, temperature (air, ground, and water), weather patterns, topography and slope, other water systems, etc.? Undoubtedly, rainfall is important, but other factors should be tested as well. Walker (1982) noted that overall geo-environmental instability was important for understanding floral biodiversity in Sahul, Sunda, and Wallacea. Perhaps high variation in other variables relating to environmental instability also results in resistance to agriculture.

Overall, the correlation between subsistence-system differences and long-term rainfall variability is sufficiently demonstrated. It would be nicer to have more data (archaeological and environmental) from eastern Indonesia and Near Oceania. It may be premature to say that rainfall variability is the primary causal factor in subsistence system changes (as I think Dewar is quite aware), but there is clearly a strong relationship.

Dewar moves beyond explaining one particular type of subsistence system to assessing different subsistence systems over a large region in relation to a particular variable. This is a useful historic/evolutionary approach that is likely to be appreciated by evolutionary ecologists and archaeologists alike. I agree with Dewar that high variability and unstable environments are important factors in the emergence of arboreal and root-crop economies in eastern Indonesia and Near Oceania (risk reduction through temporal averaging, etc.). Overall he has made an important contribution.

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It is a pleasure to have the opportunity to comment on a paper in CURRENT ANTHROPOLOGY dealing with the possible human impacts of climate variability, especially after my last interaction with anthropologists on this topic. In the late 1980s I demonstrated that the El Niño/Southern Oscillation phenomenon enhanced rainfall variability in the regions it affected, using techniques similar to those used by Dewar (Nicholls 1988, Nicholls and Wong 1990). I presented this work at a symposium in 1987 and speculated that the clear adaptations of the Australian biota to highly variable rainfall suggested that the El Niño/Southern Oscillation had been operating and affecting Australia for a long time (since it was this phenomenon that explained the highly variable Australian rainfall). I further speculated that agriculture would have been less likely to develop in areas affected by the El Niño/Southern Oscillation (and thus with a more variable climate). I noted that, globally, most of the hunter-gatherer societies that had survived into the 19th century were in regions affected by the El Niño/Southern Oscillation and suggested that this might have had something to do with the greater climate variability. This speculation was vigorously attacked by anthropologists at the symposium (I was labelled a "climate determinist"), and I deleted the section on hunter-gatherer societies from the journal paper I subsequently published (Nicholls 1989*a*) although it remains in the symposium proceedings (Nicholls 1989*b*). I note with interest, after this experience, the care Dewar has taken to avoid such attacks (note especially his final paragraph).

Dewar uses a rather different method of measuring rainfall variability from mine. Nicholls and Wong (1990) used the coefficient of variation, which Dewar regards as unsuitable partly because it is not a good measure of variability for non-normal distributions. But probability distributions of annual rainfall are often reasonably close to normal (see Dewar's figure 4 for some examples). Elsewhere (Nicholls 1988, Nicholls, Drosdowsky, and Lavery 1997) I used Conrad's (1941) definition of relative variability (mean of the absolute deviations of annual rainfalls from the long-term mean, expressed as a percentage of the long-term mean). I think that these various definitions give essentially similar results. For instance, Nicholls, Drosdowsky, and Lavery (1997) calculated the ratio of relative rainfall variability to that expected from a global relationship with mean rainfall for 341 Australian stations (fig. 1). The pattern of variability is similar to that found by Dewar (his fig. 2), with most variability on the northern coasts. Our map, which provides more information about the spatial variations in this relative variability, does indicate that even in the Australian deserts rainfall variability is higher than in similar areas elsewhere—that is, that inland rainfall is highly variable

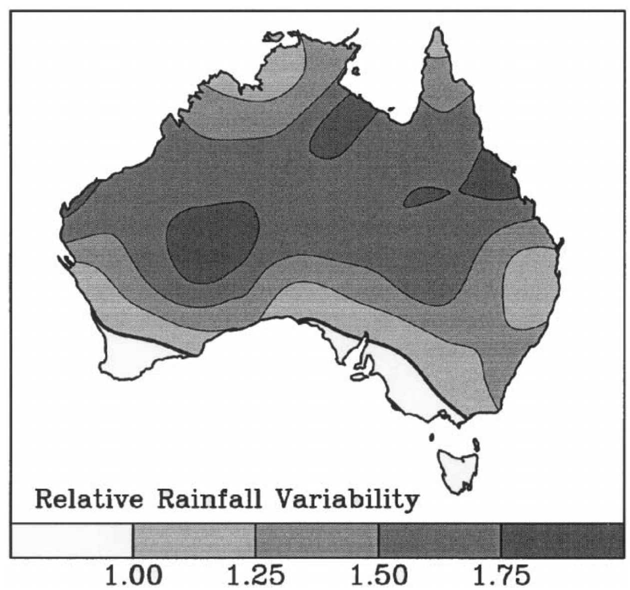

FIG. 1. *Ratio of relative variability to that expected from global relationship. The 1.0 contour is thick. The white areas indicate where rainfall variability is lower than that expected from global patterns for areas with similar annual mean rainfall. The shaded areas indicate where rainfall is more variable than could be expected from the global relationship between variability and mean rainfall. Data from 1910–92 (after Nicholls, Drosdowsky, and Lavery 1997).*

not "simply because variability is strongly correlated with aridity."

Dewar states that the "majority" of the high-variability regions (Dewar and Wallis 1999) were not in areas with a "marked El Niño/Southern Oscillation effect." I have looked again at the high-variability areas identified by Dewar and Wallis and must disagree. Of these 16 areas only 2 (southeastern China and Angola) are not identified as regions affected by the El Niño/Southern Oscillation by Ropelewski and Halpert (1989) and/or Kiladis and Diaz (1989). Though I am sure that Dewar is correct in asserting that other factors also affect variability (Nicholls and Wong [1990] identified latitude as another important factor), the El Niño/Southern Oscillation stands out as a major cause of excessive variability across the globe. I believe that much work remains to be done on the possible impacts of the variability associated with this phenomenon.

In some areas excessively variable temperatures, also caused by the El Niño/Southern Oscillation, may affect human society and agriculture. For instance, the El Niño–associated droughts of the New Guinea highlands are associated with very severe frosts which may have limited agricultural opportunities just as much as rainfall. No one appears to have looked at whether temperature variability tends to be excessive in regions affected by the El Niño/Southern Oscillation.

Dewar shows that even if variability tends to be excessive in areas affected by the El Niño/Southern Oscillation, not all such areas are affected to the same degree. Thus Indonesia is strongly affected by the phenomenon, but the variability here is less than in areas to the east and south. This spatial pattern of variability allows Dewar to postulate much more detailed impacts of this variability and thereby set the stage for more detailed tests of his hypothesis. I hope that his work will encourage more anthropologists to look at the possible impacts of excessive climate variability.

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Dewar's argument that interannual rainfall variability forms an important element of the "environmental filter" acting on crop migration in Southeast Asia is a significant contribution. His rationale for interannual rainfall variability's being a constraint on crop migration is compelling. The conclusion that interannual rainfall variability played a significant role as an environmental filter of crop migration in Southeast Asia is probably correct. However, the methodology that Dewar uses to map the present spatial pattern of interannual rainfall variability is complex and has some features that make comparisons of interannual variability between locations difficult.

The rainfall factors that determine the success or failure of a crop in a new location are differences in average growing-season rainfall and the variability of growing-season rainfall relative to the crop's requirements. Mean annual rainfall and interannual rainfall variability are probably reasonable substitutes for growing-season summary statistics. Crop migration would be difficult in environments where mean annual rainfall is less than required and interannual rainfall variability is greater than required. Dewar's figures 2 and 3 depict whether a station is in the upper quartile, middle 50%, or lower quartile of a homogeneous group. Rainfall stations in the region 30° north/south of the equator were used to create the homogeneous groups (Dewar and Wallis 1999) rather than limiting the data set to Southeast Asia. Consequently, a Southeast Asian station in a homogeneous group containing stations outside Southeast Asia may be labeled as highly variable relative to the stations outside Southeast Asia in its homogeneous group. Whether a Southeast Asian station is or is not more variable than a station outside Southeast Asia is of little relevance when discussing crop migration within Southeast Asia. The use of multiplicative weighting (Dewar and Wallis 1999) to encourage the cluster analysis to identify spatially contiguous homogeneous groups may have reduced this problem, although to what extent is not addressed by Dewar here. A potentially less confusing rendering of the spatial distribution of interannual rainfall variability is Southeast Asia would have been to map a simple measure of relative variability such as the L-moment coefficient of variation (Dewar and Wallis 1999). (Dewar notes that using the product-moment coefficient of variation can be problematic with nonnormal annual rainfall data.)

Dewar's implicit assumption that the present ("past 60 years") spatial pattern of interannual rainfall variability across China, Southeast Asia, and the Southwest Pacific represents the pattern during the period of crop migration also requires further attention. He notes the importance and long-term presence of the El Niño/Southern Oscillation in the Southwest Pacific. This phenomenon is proposed to have existed long enough to have caused Australian fauna to evolve "opportunistic" life histories in response to the resulting high interannual rainfall variability (Nicholls 1989*b*). Pook (1985), Lake (1995), and Puckridge et al. (1998) also note the role of high interannual variability of rainfall and streamflow in the life histories of Australian flora and fauna. Using data recorded during the past century Peel, McMahon, and Finlayson (2002) stratified rainfall stations by Köppen climate type and found that stations influenced by the El Niño/Southern Oscillation had 5–25% greater interannual rainfall variability than stations not influenced by it in the same climate type. McMahon et al. (1992) found that temperate Australian and Southern African annual streamflow is more variable than streamflow from other temperate regions, a result confirmed by Peel et al. (2001). Rainfall in the Southwest Pacific was subject to the El Niño/Southern Oscillation during the crop migration period, and it seems reasonable to assume that the region exhibited high interannual rainfall variability during that period.

Dewar does not suggest any possible reason(s) that the present spatial pattern of interannual rainfall variability in China and Southeast Asia is likely to be the same as that during the period of crop migration. Lamb (1982) presents evidence for substantial climate changes in China and Southeast Asia during this period. The dramatic collapse of the Indus Valley civilization around 2000 B.C. is illustrative of the impact of these changes. A temporal analysis of changes in interannual rainfall variability across Southeast Asia using palaeoclimatic sources may confirm Dewar's proposal that interannual rainfall variability is an important element of the environmental filter acting on crop migration in Southeast Asia.

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Dewar's placement of the distribution of cropping systems in the Indo-Pacific region in the context of environmental, specifically rainfall, variability is refreshing on more than one account. Although "environmental determinism" as a prime mover for culture change has long been taboo, the environment has been creeping back, but with increased sophistication, into explanatory frameworks for geographic patterns and temporal change in agriculture. The reemergence of the centrality of environmental variables is paralleled by the increasing availability of detailed data as a result of interest in global climate change and its regional manifestations and implications. The application of data on interannual rainfall reliability to the intraregional geography of subsistence strategies has important implications for cultural patterns in prehistory. For example, areas that seem to be latecomers to rice cultivation such as the southeast coast of China may now be perceived as subregions in which interannual variability in rainfall may discourage a focus on the cereal rice over plant resources less sensitive to rainfall inconsistency. Otherwise such areas may be (and usually are) seen by archaeologists as cultural backwaters.

Dewar's thesis is also satisfying from the point of view of a gardener's experience. Any gardener is constantly making decisions and testing plants on the basis of the way they respond to the conditions of the garden and how much work will be necessary to overcome the limitations of those conditions. Given a year or two of drought, plants very sensitive to several months of dryness will die unless the gardener intervenes with the watering can (until a local ordinance restricting water use cuts off even that avenue for modifying environmental conditions). The gardener quickly notices which species "do well" or at least survive to the next year despite drought or other local conditions that are less than ideal for them. After trying out that trendy new hybrid flower (substitute latest cereal crop for the ancient farmer) only to find that it withers away under even modest adversity is likely to discourage all but the most die-hard gardener from planting it again—that is, until hardier varieties become available or technological changes (e.g., automatic watering systems) appear that are affordable and fit the gardener's overall planting strategy. In the case of the traditional cereal cultivator in a nonmarket economy, if the cereal does not mature for whatever reason not only a year's food source but the seed source for planting in the following year is lost. Reliance on cultivation of annual cereals is risky business. Therefore, although he does not say so, Dewar's thesis restores some biological (and, indirectly, psychological) common sense to the discussion of why different species and cropping strategies may be preferred.

My interest in Dewar's article is mostly for its implications for the prehistory of Southeast Asia. His article is written at a macroregional scale, and I look forward to the development of his approach with more detailed data from mainland Southeast Asia and southern China. Will Vietnam, or particular portions of it, turn out to have high interannual rainfall variability like the South Chinese coast? This may have implications for some of the differences in its early agro-economic development in comparison with, say, northeastern Thailand, which according to Dewar's analysis has low interannual rainfall variability. The Philippines is another important subregion for assessing models of agricultural expansion into island Southeast Asia.

Archaeological data from Southeast Asia are beginning to become robust enough to reveal some puzzling variation in subregional development. Traditional explanations for the chronology and geography of agricultural variation using mechanisms of demographic expansion coupled with migration and diffusion are prevalent among archaeologists working on the mainland, with rice seen as the de rigueur crop of any self-respecting ancient farmer. Yet cracks are starting to appear with data that are not fitting expectations derived from the traditional models. Lively 2d-millennium-B.C. Bronze Age development in central Thailand on landscapes not suitable for wet-rice cultivation and with no clear evidence of or suitability for dry-rice cultivation suggests that a broader range of crops and cropping strategies was employed. Yet rice is well documented in northeastern Thailand at the same time. Pollen in sediment records from Thailand suggests that plant cultivation of some sort existed prior to confirmed evidence for the appearance of rice cultivation.

Dewar's article increases the number of environmental variables of which archaeologists need to be aware when creating arguments for long-term subregional agricultural development. Addition of the slowly emerging data from detailed subregional climate histories revealed in sediment sequences will enrich the empirical bases for time depth in his discussion.

Reply

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I am pleased that all but one of the reviewers agree that interannual rainfall variability may be important in the patterning of agricultural systems. All offer insightful comments or raise interesting questions to which I will respond individually, and I will also add two comments on the way in which this work may develop in the future.

White's invocation of a gardener's view of the world is in complete accord with my own view of the proximal causes of crop choice. It reminds me that the only detailed descriptions of climate in wide circulation are the "hardiness zone" maps of plant catalogs. All gardeners know that these are approximations and local features are important but also that they ignore them at their peril (or as a special challenge). Her call for a look at the relevance of interannual rainfall variation for the prehistory of mainland Southeast Asia is an example of what I had hoped would result from the publication of Dewar and Wallis (1999). Global analysis smoothes the data enough to hide important local detail but may offer clues to patterns worth exploring. Understanding regional patterns will require more and more carefully sifted data and an analysis focusing on regional topographic and climatological patterns. Yet I am certain that at the regional scale, particularly with developing regional climatic histories, interannual variation in rainfall will prove a useful tool in understanding prehistoric development.

Harris is generous in his assessment of the importance of rainfall variation for understanding the patterning of agricultural systems. He raises an issue common to many of the comments: are there other factors that must be taken into account? I certainly agree that there are many such factors, some environmental, some historical, and some an interaction between the two. He raises in particular the idea that certain types of agricultural systems are inherently more likely to expand territorially than others. Elsewhere (Harris 2003) he contrasts the expansionist early agricultural system developed in Southwest Asia (wheat, barley, pulses, sheep and goats) with other early agricultural systems. In his comment he places agricultural systems based on root, tuber, and tree crops at the "non-expansive" end of the spectrum. In general terms he may be right, but in the context of the Indo-Pacific I am not convinced: beginning about 4,000 years ago, an economic system with agricultural components that included neither grains nor pulses spread explosively across the Pacific.

Harris (2003) also makes a distinction that I consider cardinal between the spread of integrated agricultural systems and the spread of individual crops, domestic animals, and agricultural techniques. The speed with which crops, in particular, can be transferred across agricultural populations may be so great as to be effectively immeasurable by archaeologists. Perhaps the best examples are the spread of maize and sweet potatoes from the New World to some areas of the Old World. Twentieth-century crop distributions reflect both the spread of agricultural systems and later dispersals of individual crops. Given this complex history, I think that it is a mistake to infer early agricultural dispersal from modern distributions alone, without the assistance of archaeological data. With respect to the reasons for the failure of agricultural systems to establish themselves across the Torres Straits, I am fully in agreement with Harris's suggestion that archaeological evidence is what is called for.

Latinis and I clearly agree more than we disagree, although he raises questions worthy of comment. I agree that many common ways of categorizing subsistence systems obscure more than they illuminate. We need classifications for heuristic purposes, but I doubt that they can take us very far by themselves. To clarify some confusions: I did not mean to imply that small island-size was a general factor; I was paraphrasing the argument of Harris (1977; see also his comment here) about the islands of the Torres Strait. As to the historical distribution of rice, we have opposing historical sources with respect to Halmahera, but this is not unexpected given that Halmahera is adjacent to the distributional limit of rice. In fact, Maluku and Halmahera likely form an area of great interest, apparently a zone of transition in terms of both rainfall patterning and subsistence (Roy Ellen, personal communication). For Maluku in particular, Latinis (2000:50) presents anecdotal evidence that "[immigrant] rice farmers are increasingly adopting aspects of the Malukan economy, while there are fewer cases of Malukans adopting rice farming." He offers among other explanations that "it suggests the 'superiority' of the arboreal-based system in that particular environment." I agree and think that this may be an excellent opportunity for the study of agricultural adaptation.

Latinis questions whether rainfall variability is the major or even the only important variable and offers a suite of other cultural, social, and environmental variables that may be important. Again, we don't disagree: I certainly don't think that any single variable is the only important one, and I am sure that any satisfying explanation of agricultural history and development will require reference to many factors. What I intend in this paper is to identify a variable that is salient in some parts of the globe and to which human subsistence systems have had to adapt. Similarly, it has long been accepted that the northern latitudinal limit of maize cultivation in prehistoric eastern North America was related to the average number of frost-free days in the growing system. In no way can the presence of 180 or 185 frost-free days cause the adoption of maize-based agriculture, but in an area in which too many years fall short of this number it is not likely to persist.

Athens is least persuaded by my arguments. In part our differences may be due to our experiences in very different areas of the world. That root and tree crops are the "cultigens of choice in the Tropics" may seem so to an anthropologist of the Pacific, but in the areas where

I have done extensive fieldwork, Taiwan and Madagascar, even though farmers grow a broad range of tree and root crops the crops of choice are rice and millet. Across vast stretches of tropical Africa, South Asia, and Southeast Asia, grains have long been staples. This is true in areas of both high and low population density and in contexts of swidden fields as well as pondfields. Explaining the distribution of different types of staples may require examining population density and labor effort, as Athen proposes, but also environmental features and historical factors. One such historical issue is the differential "expansionism" highlighted by Harris (above and 2003).

With respect to the farmers of Pohnpei and Kosrae, I agree with Athens that an important reason for the reliance on root and tree crops is that these were probably the crops brought to the island by the initial settlers. I also agree that rainfall is abundant. I have examined the rainfall records for Kosrae, and interannual variability is indeed low. Thus, neither total rainfall nor variability is likely to be locally important in the selection of crops. A third variable, however, may be the isolation, until relatively recently, of these islands from grain-reliant regions. In the absence of an accessible source, no further explanation of a failure of a crop to appear is needed. In short, agricultural decision making is probably always a matter of both history and adaptation to environment, and in neither case need we expect things to be simple.

Haberle is undoubtedly correct that long-term climate change will often be important in explaining changes in prehistoric subsistence patterns. My paper was not a review of the prehistoric patterns of agricultural development and cultigen spread, though my argument has obvious relevance for some models of prehistory. One reason for avoiding the prehistoric data is that they are very sparse in island Southeast Asia. Haberle notes that, by some proxy records, El Niño events were subdued until about 5,000 B.P. He argues that given the early dates for rice in the Yang-tse River valley there was enough time for rice to have moved south and east beyond its historical limits before the onset of greater rainfall variability would have rendered its further spread unlikely. The problem with this line of argument is that, at least to my knowledge, there is little evidence for the arrival of rice or, indeed, of agriculture of any sort in central Indonesia before about 5,000 B.P. (Bellwood 1996), and therefore Late Holocene conditions would probably have arrived before grains had reached their modern limits. With respect to the case of Australia, I will agree that no case has been proven and we must await more and better data, both archaeological and palaeoecological.

Peel argues that, since I was interested in crop migration in Southeast Asia, it would have been preferable to have used a sample of rainfall stations limited to Southeast Asia and the western Pacific rather than a global sample. In general this may be true, but many of the grains involved, particularly the millets, have a very wide distribution across Eurasia and Africa and are thus not limited to Southeast Asia at all. This would leave an analysis of exclusively Southeast Asian and Pacific climate data open to precisely the opposite criticism.

Peel prefers a simpler measure of variability and suggests the L-moment coefficient of variation. Wallis and I have calculated this for all of the regions and stations we studied, but we chose to use the .1 quantile—the proportion of the mean rainfall falling in the typical driest year in a decade—for an ecological reason. A measure of spread like the L-moment coefficient of variation is sensitive to departures from the mean in both directions. It seems unlikely that a year with rainfall 130% of the mean would have as great an effect on farmers as a year with 70% of mean rainfall. Focusing on the .1 quantile, we were measuring the severity of the kinds of years that farmers dread most. We experimented with using the .2 and .05 quantiles, and the results were largely the same.

Along with Haberle, Peel points to the likely importance of climate change over time, and I agree that this is an important issue for future work. But he frames his argument in terms of the "period of crop migration," and I doubt that such a period ever ended. Certainly, the arrival of New World crops in the 16th century led to massive crop migrations, and I don't see why populations willing to experiment with American crops would have spurned Asian ones unless the latter were ill-suited to local conditions.

My research into rainfall variability began when I encountered Neville Nicholls's work (Nicholls 1988, Nicholls and Wong 1990), and he offered encouragement at a very early stage for which I remain grateful. I had not been aware of his earlier attempts to consider anthropological distributions in the light of rainfall variability. Differing statistics often give similar results, and it is encouraging when they do, as in the comparison of Nicholls's group's results with ours, since it suggests that the results are robust and not an artifact of method. I am not a climatologist and so will not debate the extent to which the El Niño/Southern Oscillation effect is responsible for global patterns of interannual rainfall variation.

I am confident that interannual climatic variability will be shown to be important in explaining many patterns of historic and prehistoric change as archaeologists focus on regions rather smaller than the one I have considered and are able to incorporate diachronic changes. In many areas of the Tropics the biggest limitation will be access to reliable climatic data. As smaller regions are examined, it will be possible to identify the climatic effects of topography and elevation and move the scale of analysis closer to that of a human community.

Interannual rainfall variation is not the only or necessarily always the most important form of environmental variation to which human populations have to adapt, even in the Tropics. Nicholls, for example, notes that El Niño/Southern Oscillation droughts in the New Guinea highlands are also often associated with frosts. Other forms of variation, such as variability in seasonal patterns of rainfall (noted by Peel), may also be important. Outside the Tropics, the range of variation in growing season or minimum winter temperature, for example, may be a critical factor in shaping the success of farmers or gardeners. None of these factors determine subsistence systems, but they all can, in some circumstances and at some times, impose constraints and challenges to which people must respond.

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