Late Neolithic Plant Remains from Northern China: Preliminary Results from Liangchengzhen, Shandong

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Understanding of Late Neolithic food production in China has been hampered by a lack of palaeoethnobotanical research. Studies of economic systems in China have tended to emphasize chronology, technology, individual settlements, and chance finds of plant and animal remains (that is, remains not recovered by flotation) [Chang 1986, Crawford and Shen 1998, Underhill 1997]. Setting such studies in an interdisciplinary framework is essential if we are to understand not only Late Neolithic agriculture but the origins of food production in China as well. The systematic collection of plant remains has been as integral part of a multifaceted, international archaeological investigation of the Longshan culture [ca. 2600–1900 BC] Liangchengzhen site in southeastern Shandong Province [fig. 1]. The findings reported here are the first to come from a large-scale program of systematic flotation carried out at a Chinese Late Neolithic site. The samples reported here are from the first two field seasons, 1999 and 2000. For this initial report, we document and contextualize the Longshan crops and other plant remains, explore intrasite spatial patterning, and review implications of the new data for the understanding of Late Neolithic subsistence ecology.

LONGSHAN AGRICULTURE

Most Longshan sites, distinguished mainly on the basis of shared pottery styles, are found in both warm and cool temperate zones in north-central China. This broad distribution suggests that Longshan was ethnically diverse and would have employed locally appropriate subsistence strategies. Longshan agriculture is thought to have been millet-based, with rice having little importance although it is reported from a number of Longshan and preceding Late Dawenkou sites [Underhill 1997] [table 1]. Agriculture supported a Longshan society that was ranked. Debate focuses on whether the society consisted of chieftoms or states [Liu 1996, Underhill 2002]. Settlements were hierarchically organized, and Liangchengzhen was a significant regional center within an eastern Shandong settlement hierarchy [Underhill et al. 2002]. Earthen walls surround several large sites, suggesting concern with defending economic resources. Chang [1986:250] and Luan [1997] have proposed that Longshan social differentiation was facilitated by intensive resource acquisition and production; however, until the palaeoethnobotanical details of Longshan and its predecessors have been assessed and appropriate specimens AMS-dated, this hypothesis cannot be adequately tested.

ARCHAEOBOTANICAL DATA COLLECTION AND ANALYSIS

The 1999–2000 Longshan samples reported here [table 2] are mainly from the largest excavation area [704 m²], situated on a hill about 12 m above and about 600 m
west of the Bei Xiao He (fig. 2). Seven cultural layers, 241 pits, 19 structures (probably houses), 27 burials, and numerous activity surfaces were exposed (fig. 3). We took at least one 5- or 10-liter sample whenever possible from each context. About two-thirds of the flotation samples are from the pits. Three samples are from trench T022, 460 m to the northeast. Two are from the bottom of a ditch and the third from a house foundation. The sampling strategy was designed to document variation in density, so future intersite comparisons will need to take into account potential functional relationships among contexts (see Hillman 1984). The features are mainly Middle Longshan, distinguished mainly on the basis of ceramic styles. Some contexts younger than Longshan were sampled but are not reported here. A flotation apparatus similar to the SMAP device (Watson 1976) was used to process the soil samples. Only the light fractions have been analyzed so far. Analysis followed a standard procedure outlined elsewhere (Crawford 1983).

RESULTS

The 1999–2000 flotation light fractions contain charred seeds representing cultigens, weedy annuals, wild grasses, fleshy-fruit producers, and other plants. A number of samples contain grass internode (stem) fragments. Wood charcoal occurs in negligible quantities (3.8 g). Some seeds are either “unknown” or “unidentifiable” because diagnostic traits are missing. Many unknowns are represented, but one type is particularly common.

Rice (fig. 4) is the most common cultigen by density, number, and weight. A rice grain from H93 is AMS-dated to 3,610 ± 60 cal BP or 2135 (1950) 1860 cal BC (1-sigma, TO-10206), confirming its Longshan association. Rice can be grown in a variety of ways including dry cropping, sowing in seasonal ponds, terracing, paddy fields, and combinations of these methods. We hypothesize that some form of rice production took place at Liangchengzhen. Seasonally wet habitats are common in the area today and could have been utilized during the Longshan occupation. (Local farmers have tried to grow rice near the site but failed for lack of sufficient water.) Sedges, common in wet habitats, occur in five contexts but mainly in the G022 ditch sample. Phytoliths of the common reed that grows in disturbed, damp, or wetland habitats (Phragmites sp.) have also been identified in the samples (Jin et al. n.d.). The rice grains are, on average, significantly smaller (4.0 mm by 2.0 mm) than either wild rice or modern rice cultigens. The rice may have
TABLE 1
Chronology of Late Neolithic Sites with Crop Remains

<table>
<thead>
<tr>
<th>Culture/Period and Site</th>
<th>Rice</th>
<th>Millet</th>
<th>Wheat</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhuanglixi g, x, –</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>Zhaojiaoshu g, f, b, g</td>
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<tr>
<td>Tenghualuo g, p, –</td>
<td>–</td>
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<tr>
<td>Yungiaquan g, i, x, i</td>
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<tr>
<td>Yaowangcheng</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>Shantaisi g, f, b</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>Jianxin</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Sanlihe</td>
<td>–</td>
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<td></td>
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<tr>
<td>Yuchisi</td>
<td>–</td>
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<td></td>
</tr>
</tbody>
</table>

Note: g, grain; p, phytoliths; i, impressions; f, foxtail millet; b, broomcorn millet; x, unspecified millet.

been grown under stress, and therefore we are keeping open the possibility that it was grown in dry fields.

Millet are the only other cultigens present in significant quantity, but they occur at lower density than rice. Broomcorn millet is rare, found mainly in pit H39. Foxtail millet accounts for 94% of the millets and is found throughout the site. One common type of millet-tribe seed in the samples is morphologically identical to foxtail millet but significantly smaller.

Two bread wheat grains have been identified. Neither has been AMS-dated; however, one is from inside a Longshan pot in pit H42 while the other is from a deep posthole near pit H65. These grains appear to be the oldest examples of wheat so far found in eastern China. Undated wheat is reported at the Erlitou-period (ca. 1900–1500 BC) Zaofiaoshu site in Luoyang, Henan, along with possible barley [Ye 2000]. The photograph of possible barley from Zaofiaoshu [Ye 2000: pl. 22] does not illustrate a grass, and therefore barley is not yet confirmed from Longshan or its immediate successor, Erlitou.

Seeds identical to those of wild soybean are found in most contexts (table 2, fig. 5). The specimens (about 6.0 by 4.0 by 3.6 mm) are significantly smaller than the earliest known domesticated soybeans [Crawford and Lee 2003]. Wild soybean grows throughout north-central China [Hymowitz and Singh 1987] in disturbed habitats. Although seed size distinguishes domesticated from wild types in collections postdating 1000 BC, size should not be the sole distinguishing trait of cultigen soybeans. Wild soybean pods naturally split to discharge the beans whereas domesticated ones do not. No pods have been recovered, nor do we expect to find any, and therefore we cannot categorically identify the beans as wild. Nevertheless, if soybean was not purposefully grown as a crop at Liangchengzhen it was probably productive as a result of local anthropogenesis. Soybean seeds are reported from at least eight other sites in China; most postdate the Longshan (Ye 2000), and all are small.

Adzuki bean occurs in flotation samples from layers near pit H65 and from the G022 ditch. The seeds are smaller [4.0 to 4.2 long by 1.1 to 3.3 mm wide] than those of the modern cultigen but larger than wild adzuki and are in the size-range of similar beans from the Daundong site, South Korea [Crawford and Lee 2003:91], that we suggest are an early cultigen. This is the first report of this bean from Neolithic China, and until we have larger samples from a broad geographic area we can only indicate that the plant was present in Liangchengzhen anthropogenic habitats. Wild adzuki bean is widely distributed in East Asia (Yamaguchi 1992).

The most common weedy annuals represented in the samples are millet-tribe grasses. Two main morphological types are present: a green foxtail type and a panicgrass type. The two are distinguished primarily on the basis of embryo size. Embryos of the former extend more than half the length of the grain whereas embryos of the latter are significantly shorter. Specimens with hulls attached are green foxtail grass, distinguishable on the basis of the surface pattern of the hulls. Other weedy plants are rare in the samples but may also have been utilized as sources of greens and grain.

Spatial distributions

Variation in the contextual distribution of plant remains has an impact on intersite comparisons as well as on an understanding of the function of structures and plant processing. As many as 30 crop-processing steps have been identified in Turkey and correlated with archaeological sites in North Wales [Hillman 1984]. We are not yet able to do this type of detailed analysis; however, significant patterns are evident, although their meaning is not yet clear. Large Longshan settlements tend to have residential areas including elite and lower-class houses, pits containing refuse, ritual pits, and larger features [such as walled enclosures and surrounding ditches that may have been moats]. In the main excavation area at Liangchengzhen, context types are diverse but appear to be mainly domestic. The two samples from trench T022, from a ditch that is a possible moat and from a nearby house foundation, may also represent domestic waste.

Charred seed assemblages in the seven context types summarized in table 2 have significant differences. The
TABLE 2
Summary of Liangchengzhen Flotation Samples

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Activity Surfaces</th>
<th>Burials</th>
<th>Houses</th>
<th>Cultural Levels</th>
<th>Post-holes</th>
<th>Go22</th>
<th>Pits A</th>
<th>Pits B</th>
<th>Pits C</th>
<th>Pits D</th>
<th>Total Pots</th>
<th>Total</th>
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<td>12</td>
<td>19</td>
<td>43</td>
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<td>9</td>
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<td>13</td>
<td>172.3</td>
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<td>358.7</td>
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<td>Setaria italica</td>
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<td>Barnyard grass</td>
<td>Echinochloa crusgalli</td>
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<td>21</td>
<td>4</td>
<td>2</td>
<td>39</td>
<td>2</td>
<td>40</td>
<td>20</td>
<td>12</td>
<td>–</td>
<td>110</td>
<td>142</td>
</tr>
<tr>
<td>Total seeds</td>
<td>63</td>
<td>24</td>
<td>113</td>
<td>642</td>
<td>130</td>
<td>847</td>
<td>2,137</td>
<td>71</td>
<td>24</td>
<td>980</td>
<td>3,212</td>
<td>52</td>
</tr>
<tr>
<td>Seed Density [no./liter]</td>
<td>0.51</td>
<td>0.46</td>
<td>0.59</td>
<td>1.61</td>
<td>2.60</td>
<td>65.15</td>
<td>12.40</td>
<td>2.27</td>
<td>0.07</td>
<td>1.50</td>
<td>2.64</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The highest density of remains including all classes of plants is in the ditch [level 4]. Intermediate densities occur in pits, postholes, and cultural levels. Among the pits, group A, mainly represented by H65 and 93, has the highest density of seeds, particularly rice. Pit H93 has an abundance of ash that, along with its multilayered stratigraphy, indicates that, while probably a long-term storage pit, it later accumulated refuse. Group C has very few seeds, but these contexts are associated with a group of house walls, and the function of the pits here is difficult to assess. Activity surfaces, burials, and houses have low seed densities, particularly of cultigens. Among the few seeds in these contexts, wild grasses predominate. Pots occur in all contexts and have the lowest density of remains. A range of seed types is found in them. Pots likely contained few if any charred remains when they were disposed of.

The fact that the contexts with the highest densities
of charred seeds are in cultural levels, among group A samples associated with few structural remains, and in a ditch indicates that charred seed disposal tended to occur outside architectural structures. Weeds tend to be distributed throughout the site while crops are not. Crops are obviously food, so food remains may have a distribution distinct from other plant remains. We cannot rule out the possible food use of some of the weedy grasses, but it seems unlikely. In Senegal, for example, pearl millet coexists with swarms of hybrids of the cultigens with weedy and wild forms (Harlan 1989a). Although farmers recognize these hybrids as significant, they are not harvested for food. Wild grasses in Africa tend to be used in nonagrarian contexts (Harlan 1989b). A more likely explanation is that some of the remains are from spent dung fuel disposed of outside the structures. Grasses, grass stem fragments, and wild legumes are, in some cases, likely the remains of dung, especially when little wood charcoal is present (Miller 1984). Cultigen seeds have a significantly lower representation in dung samples (Reddy 1999). Seeds of wild grasses, chaff, and grass stem fragments are found in samples from the southern units as well as in the ditch sample. The almost complete absence of wood charcoal from the flotation samples indicates that wood was not an important fuel. The higher density of weed seeds in structures is consistent with the remains’ being of fuel rather than food.

**Discussion and Conclusions**

Flotation samples from Liangchengzhen clearly represent an agricultural economy that produced rice, millet, and probably wheat. Other potential crops include soybean and adzuki bean. Anthropogenic weeds associated with agriculture are common. Rice appears to have played a much more significant role in the Shandong Longshan economy than previously suspected. From the limited perspective of the raw weight and density of the rice and millet seeds, it may have been more economically important than millet at Liangchengzhen. The implications of these findings are important, because the assumption until recently has been that broomcorn and foxtail millet were the major and possibly the sole grains in most areas of northern China. Rice can be grown in
northeastern China today, so there was probably no climatic impediment to its being grown at Liangchengzhen, particularly because until the late Longshan it may have been warmer than today. The climate may also have been considerably wetter during much of the Longshan, when the monsoon belt had apparently shifted north, leaving South China drier than today (Zhou et al. 2004:47). A cooling and drying trend seems to have developed during the late Longshan period, ca. 2000 BC (Kong et al. 1999:62), probably representing the local end of the Hypsithermal or Holocene Optimum. In some areas the warm period may have persisted. Textual and material evidence for plants and animals adapted to warm, moist conditions has been found farther north and west of Liangchengzhen at Anyang, the last capital of the Shang dynasty [ca. 1200–1046 BC (Qiu and Cai 2001)]. Climate is difficult to reconstruct because of the degree to which anthropogenesis affects the mid-Holocene pollen record today (Zhou et al. 2004:47).

The dominance of foxtail millet over broomcorn millet in the samples probably indicates that broomcorn millet was not important to the lower Huang He valley Longshan people. Contemporary agriculture varies as both elevation and aridity increase with distance from the coast. Rice is important today only in the south and east sectors of the Longshan region. Although millet is rare in the region today, broomcorn millet was historically more important in the west while foxtail millet was common in the east. Rice is present at the Longshan Shantaisi site in Henan but in insignificant quantities (Crawford, Leng, and Lee 2001). Broomcorn millet is much more abundant at Shantaisi than at Liangchengzhen. We suggest that historical crop distributions had developed by Longshan times in the Huang He basin.
Overall, crop remains occur at about one-third the density of weedy plant seeds, particularly grasses. A few contexts contain mainly cultigens, while others contain mainly weeds and still others have both. Intersite comparisons will need to take into account such contextual variation. The types of remains recovered in and near areas where food was regularly prepared and consumed by households will differ from those found where periodic or ritual events were carried out. Few crop remains are found inside structures. Food preparation such as steaming or boiling may work against the preservation of grains after cooking, and ceramic tripod vessels suitable for steaming grains or preparing gruels are common at Liangchengzhen. The relatively low density of cultigens throughout the site (excluding H93) may mean that we are recovering mainly the charred waste from grain processing (tail grain, weed seeds, chaff) or the waste from fuel.

Few economically important wild plants are represented in the samples. In egalitarian communities with mixed economies such as the Sakush-Kotoni River site in Japan, a wide range of wild plants is represented, although cultigens and weedy annuals still dominate the plant remains [Crawford 1986]. Some of the weeds such as chenopod and knotweed have edible and productive seeds and greens. In the central mountains of Taiwan, chenopod was planted in foxtail millet fields [Fogg 1983: 100]. Early agricultural regimes may have differed from modern analogues in including some of these plants as crops. A few seeds of wild, fleshy fruits are represented, but their use is difficult to assess. Most are productive in anthropogenic habitats.

Crops such as hemp (Cannabis sativa) and Chinese cabbage (Brassica chinensis), reported from Neolithic sites in northern China [Chang 1976, Crawford 1992, Underhill 1997], have not been found at Liangchengzhen. Although mustard-family (Brassicaceae), seeds have been recovered, they are in poor condition and difficult to identify more specifically. Residue analysis of pottery suggests that rice was used for the preparation of alcohol [Chinese-American Rizhao Liangcheng Region Collaborative Archaeological Team n.d.].

Not only does rice appear to have been more significant for eastern Longshan people than previously suspected but the presence of wheat foreshadows more modern agriculture based on both rice and wheat. Wheat is rare at Liangchengzhen and was likely just being introduced to the region. Without earlier samples for comparison, we cannot know whether rice, first domesticated in the Yangzi Valley, was also new to the Liangchengzhen Longshan people. Judging from its abundance, it probably had become a significant resource in Shandong at an earlier time. Introduced crops can, of course, have a significant impact. Maize, for example, was introduced to existing agriculture in the North American Midwest. Production increased as a result and
maize became a significant crop by AD 800, signaling intensification that supported complex socioeconomic systems such as the Mississippian (Fritz 1992, Kelly 1992). Initially, maize added to the balance of crops, but by AD 1400 it was the predominant one. Diversification is effective in risk reduction, but subsequent specialization in a few dominant crops can increase risk. The low diversity of crops at Liangchengzhen suggests that specialization was developing. To what extent increased production and risk management are evident there is a question we hope to address. Socioeconomic processes during the Middle and Late Neolithic such as expanding regional exchange systems may have facilitated the introduction of new crops to the area. The expansion of rice agriculture and the introduction of wheat during the Late Neolithic no doubt represent increased contacts among peoples from different areas.

An issue requiring further examination is Late Neolithic site formation processes in Shandong, including which activities of the site’s inhabitants (such as various food-processing methods and cooking technologies) could have caused some plant remains to be preserved by carbonization while others were not. The fact that there is distinct spatial variation in the densities of preserved carbonized seeds at Liangchengzhen argues strongly for the value of systematically collecting large quantities of flotation samples from diverse areas during excavations of late prehistoric sites in China. Our continued analyses of these samples in conjunction with other remains will help us to understand the nature of the subsistence economy at the regional center over time. One issue that we will address further, utilizing data on size, type of soil, and the nature of other remains such as different kinds of ceramics, is functional variation among the numerous pits and surfaces.

References Cited


Dung in the Desert: Preliminary Results of the Negev Holocene Ecology Project

In their investigations of caves and rockshelters in the Near East, archaeologists studying prehistoric times have all too often had to deal with the accumulated dung of thousands of years of sheep and goat herding. The solution has generally been summary—the dung is removed as quickly as possible, with little or no documentation, collection, sampling, or analysis (but see Simms and Russell 1997, di Lernia 2001 for significant exceptions). This is unfortunate. Preliminary results of analyses of Negev Holocene rockshelter deposits, pri-

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1. The Negev Holocene Ecology Project, a joint endeavor of the Department for Historical Ecology of the Severtsov Institute for Ecology and Evolution of the Russian Academy of Sciences, the Mitzpe Ramon Science Center, and the Archaeological Division of Ben-Gurion University, has been supported by grants from the Russian Academy of Sciences, the Israel Ministry of Science and Technology, and the Mitzpe Ramon Science Center. We thank E. Mazor and B. Krasnov for arranging the research in the Negev Desert. We are very grateful to I. Khokhlova and G. Shenbrot for their help. This research was funded by Blaustein Institute for Desert Research and Ramon Science Center [Israel], the Russian Fund for Basic Research [Grant No 03-04-49333], and the Russian programs “Origin and Evolution of the Biosphere,” “Scientific Basics of Conservation of Biodiversity of Russia,” and “Fundamental Basics of Biological Resources Management.” We are grateful to the licensing authorities, the Israel Antiquities Authority, and the Israel Nature Preservation and Parks Authority for both permission to conduct the research and gracious help in carrying it out. We also thank six reviewers for current Anthropology for comments that helped us to strengthen this report significantly.
to as high as 200 mm per year, around Loz, to less than 75 mm per year, at the Nekarot Rockshelter (Stern et al. 1983: fig. 9.14; also Evenari, Shanan, and Tadmor 1982: 32, fig. 13). The variation is effected primarily by altitude. Ancient rainfall varied significantly, perhaps rising to as high as 200 mm/year or more during wet episodes of the Early and Middle Holocene. The basic Irano-Turanian vegetation community seems to have increased in density in these periods rather than being replaced (e.g., Frumkin et al. 1994; Goodfriend 1990).

The rockshelters are located on ledges beneath overhangs on ridges or plateaus or on cliff faces. Loz is the exception, with more cavelike characteristics including a wider interior space and an open chimney through the vault. All five were known from previous surveys and chosen for sampling for their potentials for paleoenvironmental reconstruction, primarily on the basis of depth of deposits. Sediments are dominated by dung layers, with varying quantities of ash, charcoal, gravel/sand, and stone. Although bones have been recovered, with the exception of materials from the lowest levels of the Loz site (not associated with the dung layers) and microfauna (still being analyzed), they are all virtually unidentifiable splinters. The primary distinction that can be drawn between major sedimentological units is the presence/absence of the dung of domestic herd animals (sheep/goat), with nondung layers being dominated by sand/gravel and stones. We distinguish between “dung” and “feces” on the basis of compaction and agglomeration. For our purposes, feces are isolated pellets, whereas dung occurs as packed matrix. Ash and hearth deposits may intermingle with dung layers as well as appearing in nondung deposits. Notably, phytoliths appear in both the dung and the associated ash deposits.

Although detailed compositional analyses of the dung layers reported on here are still under way, such deposits (in rockshelters) are readily identifiable by the heavy organic matrix, often including identifiable pellets and out-

<table>
<thead>
<tr>
<th>Location</th>
<th>Lab. Code</th>
<th>Uncalibrated Yr. BP</th>
<th>Calibrated Yr. BC/AD</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashkarim Layer V</td>
<td>IEMAE-1318</td>
<td>423 ± 4</td>
<td>AD 1438–1478</td>
<td>Late Middle Ages</td>
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<tr>
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<td>IEMAE-1317</td>
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<td>AD 1646–1948</td>
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<tr>
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<td>IEMAE-1316</td>
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<td>5983–5731 BC</td>
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</tr>
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<td>IEMAE-1331</td>
<td>Modern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer I</td>
<td>IEMAE-1330</td>
<td>Modern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer II</td>
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</tr>
<tr>
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<td>2044–1743 BC</td>
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<td>1942–1644 BC</td>
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<td>2463–2202 BC</td>
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<tr>
<td>Layer VII</td>
<td>IEMAE-1325</td>
<td>3,780 ± 120</td>
<td>2456–1984 BC</td>
<td>Early Bronze III–Middle Bronze II</td>
</tr>
<tr>
<td>Layer VIII</td>
<td>IEMAE-1298</td>
<td>4,873 ± 97</td>
<td>3757–3539 BC</td>
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<tr>
<td>Ramon 1</td>
<td>IEMAE-1319</td>
<td>6,050 ± 118</td>
<td>5204–4785 BC</td>
<td>Late Pottery Neolithic</td>
</tr>
<tr>
<td>Layer VIII</td>
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<td>6203–5934 BC</td>
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</tr>
<tr>
<td>Nekarot</td>
<td>IEMAE-1321</td>
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<td>AD 1264–1287</td>
<td>Middle Ages</td>
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<tr>
<td>Layer II</td>
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<td>891 ± 92</td>
<td>AD 1024–1256</td>
<td>Middle Ages</td>
</tr>
<tr>
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<tr>
<td>Layer III</td>
<td>IEMAE-1324</td>
<td>8,473 ± 157</td>
<td>7601–7352 BC</td>
<td>Pre-Pottery Neolithic B</td>
</tr>
</tbody>
</table>

Note: All assays were performed on plant remains and charcoal. Period attribution is by reference to dates, not material culture. The discrepancy between the date and the late Pleistocene material culture at Loz results from mixing.
Fig. 1. The Central Negev Highlands, showing sites mentioned in text.

lines of compressed pellets in the compacted layers (fig. 2). Colors are usually dark browns and blacks, although gray ash also occurs when the dung has been burnt. Notably, even the earliest of the dung layers described here (ca. 6000 BC) still retained the distinctive (musty) odor of desiccated dung, recognizable to anyone familiar with modern sheepherding.

Identification of the species responsible for the accumulation of the dung is based on several criteria. First, the shape of the pellets (see di Lernia 2001) is easily recognizable and distinctive to sheep and goat in the region. Larger herd animals, such as camels, cattle, donkeys, horses, or onagers, produce much larger (and also recognizable) pellets. Gazelles produce pellets that are rounder and half the size or smaller. Dung produced by other animals, for example, porcupine, hyrax, or hyena, is also readily differentiable from sheep/goat dung. Second, the dung layers reported on here exhibit clear visual and textural similarities from the top to the bottom of each section, and the top layers are clearly the result of recent Bedouin sheep/goat herd accumulations (cf. Simms and Russell 1997). It is reasonable to assume that they represent similar phenomena. Finally, only a limited number of species could have inhabited Negev rockshelters intensively enough to produce layers of dung. Larger animals, such as camels, could not even have entered some of the shelters. *Capra ibex* (ibex) have been observed clustering beneath rockshelter overhangs
during rain, and there is evidence for their occasional presence in the rockshelters in small numbers and for short periods. Procavia capensis (hyrax) and Hystrix indica (porcupine) have also been found in some of these shelters, but, again, their dung is identifiable. The small group sizes of some animals, such as porcupine or even hyena, also argues against them as agents of the dung accumulations noted here. Herds of sheep and goat are the most obvious candidates (although obviously this by itself is not a sufficient defining factor).

The domestic status of these herds still needs to be established. This issue can be separated into two questions, human manipulation of the herds (penning, as it were) and the specific status of those herds. Work on dung deposits in the Gobi Desert and in the Caucasus shows that a high rate of dung accumulation, high compression, presence of artifacts, and evidence for fire [charcoal, ash] are characteristic of rockshelter dung deposits accumulated by domestic herds. In contrast, wild animal dung accumulations show lower rates of accumulation, less compression, and greater preservation of individual pellets [Dinesman, Kiseleva, and Knyazev 1989; Knyazev and Savinetsky 1992]. Of course, these features are in reality associated with penning, and one cannot rule out the possibility of the penning of wild animals, as at Uan Afuali Cave in Libya [di Lernia 2001]. In other words, the dung accumulations in the Negev rockshelters described below reflect human manipulation and exploitation of sheep and goat but not necessarily domestic status. In this context, the absence of such accumulations during earlier periods, before people herded animals, argues against the possibility that these layers were the result of herd aggregations without human involvement.

The argument for domestic status is contextual. Pre-Pottery Neolithic B faunal assemblages from sites in the Negev and Sinai show no bones of Capra aegagrus [wild goat] or Capra hircus [domestic goat], the ungulate assemblages consisting of Gazella and C. cibex [e.g., Bar-Yosef 1984, Tchernov and Bar-Yosef 1982, Dayan et al. 1986]. Ibex are behaviorally unsuited to herding and penning. In general, domestic sheep and goat were introduced into the southern Levant in the eighth millennium BC [Davis 1984]. Diffusion into the Negev and Sinai occurred later [Rosen 2002, Goring-Morris 1993], as did the morphological changes associated with the later stages of the domestication process [e.g., Horwitz et al. 1999]. Thus it is likely that the dung was deposited by domestic sheep and goat penned by human shepherds.

The use of caves and rockshelters for sheltering domestic herds is still a common occurrence today throughout the Near East. Obviously, the rockshelters provide protection from the elements during inclement weather, and clustering of the animals in the enclosed space of the shelter undoubtedly preserves body heat. The presence of occasional terrace and enclosure walls in these sites suggests that they also served as convenient corrals.

### The Sites

**Ramon I.** The Ramon Crater (makhtesh) is a deep erosional cirque defined by steep cliffs of hard limestone rocks in its upper layers. The Ramon I Rockshelter is located in the upper cliff face of the north wall of the crater, approximately 200 m west of the ascent leading out of the crater. It faces south, stretches some 200 m along the face of the cliff, and rarely exceeds 2 m in width. It was first discovered and tested in 1981 by Rosen (1994:41, 37’), who reported Byzantine ceramics and an associated terrace wall in the rockshelter itself and Natufian and Harifian (Late Epipaleolithic, Terminal Pleistocene) lithic artifacts scattered on the slope beneath it. A small sounding down to bedrock, $2 \times 1 \times 1$ m, was opened, and a tabular scraper attributable to the late fifth to third millennia BC was recovered in the lower levels of the pit. In 2001 the sections of this pit (fig. 3) were cleaned and sampled. The profile can be divided into eight layers, with a sedimentological disconformity between layers VII and VIII. The primary component of all eight layers is sheep/goat dung, with layers III, V, and VII showing higher proportions of hearth ash.

Two points are of particular note. First, layers IV and VI are harder, cemented or consolidated layers of dung and ash. On the basis of ceramic associations these layers can be dated roughly to Byzantine or Early Islamic times (second half of the first millennium AD). This cementation or consolidation is present in only two other rockshelters in the highlands, the Besor Rockshelter and Zalzal Cave. Study of these two sites, explored only in 2002, is still in its preliminary stages and will not be reported on here, but in both cases the consolidation phenomenon seems to be associated with late antiquity. It has not

---

**Table 2: Rock Shelters and Attributes**

<table>
<thead>
<tr>
<th>Grid</th>
<th>Altitude [m amsl]</th>
<th>Approximate Rainfall [mm/year]</th>
<th>Direction of Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loz</td>
<td>1092/9869</td>
<td>&gt; 100</td>
<td>West</td>
</tr>
<tr>
<td>Ashkarim</td>
<td>1095/9863</td>
<td>&gt; 100</td>
<td>South</td>
</tr>
<tr>
<td>Nekarot</td>
<td>1266/9926</td>
<td>&lt; 75</td>
<td>East</td>
</tr>
<tr>
<td>Ramon I</td>
<td>1225/9926</td>
<td>75–100</td>
<td>South</td>
</tr>
<tr>
<td>Atzmaut</td>
<td>1314/9032</td>
<td>75–100</td>
<td>South</td>
</tr>
</tbody>
</table>
Fig. 2. Sheep/goat dung pellets, fragments of pressed dung, and plant remains from Ramon 1 Rockshelter, level 8, depth 92–97 cm.

been encountered in other periods and therefore may reflect either the particular environmental circumstances of the period or perhaps human behaviors specific to its societies.

Second, the presence of clearly identifiable sheep/goat dung pellets in the lowest levels of layer VIII is associated with radiocarbon dates of $6,050 \pm 118$ BP, calibrated to $5204–4785$ BC 1-sigma, and $7,213 \pm 84$ BP, calibrated to $6203–5934$ BC 1-sigma (Stuiver and Reimer 1993), both Pottery Neolithic in date. The high density of these pellets and their compression into pockets of compacted dung are strongly indicative of penning, almost undoubtedly of domestic sheep and goat. Given the virtual absence of preserved animal bones from Pottery Neolithic sites and the paucity of Pottery Neolithic sites in the Negev Highlands in general, this dung layer constitutes the earliest direct evidence for the presence of domestic herd animals in the Negev Highlands.

Nekarot. The Nekarot Rockshelter is located beneath a plateau overhang at the head of a small wadi tributary of Nahal Nekarot about 1 km south of the Ramon Crater. It faces east, stretches some 30 m beneath the overhang, and is up to 5 m in width. It was discovered in 1980 during a survey conducted under the auspices of the Negev Emergency Survey (Rosen 1994:101, 617). Test excavations conducted in 1991 (Goring-Morris et al. 1998, Belfer-Cohen et al. 1991) revealed some 40 cm of Ramonian (Epipaleolithic, ca. 13,500 BC) deposits beneath a major roof fall which was, in fact, responsible for the preservation of the Ramonian horizon.

Holocene sediments accumulated above the rockfall and adjacent to it, leaving natural sections. These were cleaned back and sampled and are the focus of this study. Four basic layers are defined (fig. 4). The upper two, layers I and II, constitute a continuum and are made up of sheep/goat dung in varying states of compression and with varying quantities of hearth ash. Layer II can be subdivided into three substrata defined by variations in quantities of hearth ash, essentially ash lenses within the general dung layer. A sedimentological break defines the contact between layers II and III, with layer III showing a higher proportion of gravel and ash and lower densities of pellets. Given this low density of pellets and apparently low rate of accumulation and the high density
of gravel in layer III, these accumulations are unlikely to be those of domestic animals and probably represent the use of the shelter by *Capra ibex*. They certainly do not reflect penning of herds. Planned studies of parasite remains from the dung layers may provide more detailed information on differences between domestic and wild remains (Savinetsky and Khrustalev 1991).

The ash lenses in layer III are undoubtedly anthropogenic, probably reflecting ephemeral human occupations. The radiocarbon determination of 8,473 ± 157 BP falls into the Pre-Pottery Neolithic B horizon and accords with the isolated discovery of a blade-based arrowhead fragment from the site. As mentioned earlier, archaeological sites dating from this period in the Negev and Sinai show only the remains of wild animals (e.g., Bar-Yosef 1984, Tchernov and Bar-Yosef 1982, Dayan et al. 1986). With the exception of a small lens with bones and charcoal at 75 cm, layer IV, from 70–80 cm in depth, is sterile, consisting entirely of gravels and sands.

Beyond the sedimentological history of the rockshelter, the radiocarbon dates in layers I and II, in association with dung layers, suggest the later use of the cave by shepherds from the late Byzantine/Early Islamic period through the Middle Ages.

**Atzmaut.** The Atzmaut Rockshelter is located in the upper cliff face of the north wall of the Ramon Crater at the head of the Atzmaut Ascent, on the edge of the town of Mitzpe Ramon. It faces south and geologically occupies the same seam between two limestone formations as the Ramon I Rockshelter. The shelter has been known for many years and was partially destroyed in the 1950s with the construction of the paved road leading through the crater. This destruction left an open section, visible from the road, which was cleaned and tested. Thus, the original
Fig. 4. Section and schematic of the Nekarot Rockshelter. Radiocarbon dates are uncalibrated. 1, pressed dung; 2, friable ash; 3, burnt dung with charcoal inclusions; 4, gravel with ash and charcoal; 8, friable gravel, 9, rock; 12, plant remains (twigs, fruits, etc); 13, animal bones; 16, lens filled with animal bones; 17, ungulate feces; 18, charcoal.
dimensions of the shelter were impossible to determine. Previous survey revealed Early Bronze Age ceramics and organic remains [personal observation, SAR].

The profile (fig. 5), 1 m in depth, can be divided schematically into eight sedimentologically defined layers. With the exception of layers IV and III, the primary components of the profile are sheep/goat dung and interspersed ash deposits. The transition between layers IV and V is marked by a sedimentological discontinuity, perhaps reflecting a change in the shape of the rockshelter [induced by rockfall]. Thus, in contrast to layer V, whose primary matrix is pressed dung deposits, layer IV is a sterile gravel layer and is succeeded by layer III, also dominated by gravels. In fact, the feces present in layer III seem to be from hyrax, with sheep/goat dung appearing again only after another stratigraphic break, between layers II and III.

The radiocarbon sequence suggests two primary series of occupation separated by a major hiatus. The early series is Bronze Age in date, beginning in the early stages of the Early Bronze Age [in accordance with previous assessments based on ceramics in the region [Sebbane et al. 1993]] and extending through the beginning of the second millennium BC, Middle Bronze Age II. This in itself is important in that no artifactual remains from this period have ever been recovered from the Central Negev. The minor stratigraphic reversal between the two dates in layer V in fact strengthens the sense that these indeed fall into the early second millennium BC; statistically the dates do not differ significantly.

The two dates from layer VII are also important in that they too seem to fall into a settlement gap in terms of material culture, the end of Early Bronze Age III. How-

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**Fig. 5.** Section and schematic of the Atzmaut Rockshelter. Radiocarbon dates are uncalibrated. 1, pressed dung; 2, friable ash; 3, burnt dung with charcoal inclusions; 6, consolidated sediment of gravel and dung; 8, friable gravel; 10, recent pressed dung; 11, consolidated sediment of gravel and fine-grained sediments; 12, plant remains (twigs, fruits, etc.); 14, pebbles; 17, ungulate feces; 20, stone.
ever, given the stratigraphic reversal associated with these dates and the confidence limits associated with the method, layer VII could also be attributed to the period from 2200 to 2000 BC, the Intermediate Bronze Age, a period well attested in the archaeology of the region. As above, the difference between the two dates is not statistically significant.

The upper series of three dates, associated with layers I and II, is recent in origin. The earlier date, at the base of layer II, fits well with the early-middle phase of recent Bedouin tribal penetration of the Negev, which has continued into recent times.

**Loz.** The Loz Rockshelter is located on the upper part of a steep slope overlooking a tributary of Nahal Loz. It faces west and is more cave-like than the other shelters described here, measuring 10 m in length and 9.7 m in width. A 1 x 1-m test pit was excavated in 2001 (fig. 6). Layer I consists of an accumulation of bird droppings beneath a vertical chimney in the cave vault. Layers II and III are dung accumulations, with layer III also con-
taining ash, charcoal, and gravel. The radiocarbon dates on the dung at the base of layer II indicate a recent (early-nineteenth-century) Bedouin occupation. The transition between layers III and IV is marked by the disappearance of dung as a component in the sediment matrix, a concomitant decrease in charcoal, and a significant increase in gravel and large stones. These last perhaps reflect the final collapse of the chimney from the vault. Beneath this, layer V is a burnt layer which seems to represent hearth scatters, and layers VI and VII show varying quantities of ash, charcoal, and gravel, with layer VI showing an increase in animal bone. Although layer VII contained isolated pellets of feces, these were rare and certainly are not indicators of penning. As in Nekarot layer III, these are interpreted as feces of ibex. Layer VIII is a sterile gravel layer.

Twelve flint artifacts were found in association with layer V: a chip, five bladelet fragments, a complete bladelet, a microburin, two chunks of heat-shattered flint, a small flake, and a thick burnt broken flake. All but the two flakes are on semitranslucent brown-gray flint. In addition to these, two scrapers, a bladelet, and a broken flake were found near the entrance to the shelter. Finally, a *Dentalium* bead and two bird-bone beads were also found in association with layer V. These artifacts are best associated with the Mushabian-Ramonian-Natufian horizons of the Middle to Late Epipaleolithic, ca. 14,000 to 10,500 years BP. They are therefore in significant disagreement with the radiocarbon determination of 6,978 ± 97 BP at the base of layer VII, suggesting some kind of intrusion or mixture.

Ashkarim. The Ashkarim Rockshelter is located on the upper slope of the ridge above Nahal Oz. The rockshelter faces south, stretches 15 m along the ridge, and is only 1.5 m wide. The small test pit, 0.5 × 0.5 m, was excavated to a depth of 28 cm beneath the surface before encountering sterile gravels. Although five layers are distinguished (fig. 7), all are facies of dung deposition, with varying degrees of compression and varying quantities of ash, charcoal, and gravel. The calibrated radiocarbon determination at the base of the pressed dung accumulation of layer V, AD 1438–1478, again falls into one of the periods for which we have no material culture presence in the Central Negev.

**Discussion**

In terms of the historical/archaeological sequence in the Negev Highlands, two primary conclusions may be drawn from the above materials. First, the penning of domesticated herd animals, sheep and goat, is clearly present in the Negev as early as 6000 BC, the Early Pottery Neolithic. Prior to this period there is no good evidence for exploitation of the Negev rockshelters by shepherds. Although sites from this Pottery Neolithic period are rare in the highlands, they are present in surrounding areas such as the dunes of the western Negev (e.g., Goring-Morris 1993, Burian and Friedman 1975, Rosen 2002) and the southern Negev (Goring-Morris and Gopher 1983, Avner, Carmi, and Segal 1994). This, of course, suggests that the region served as a grazing zone during this period as opposed to a settlement or camp zone proper. In any case, the dung from Ramon I layer VII constitutes the earliest direct biological evidence for herding of domestic ungulates in the Central Negev and suggests that one of mechanisms for the introduction of domestic herd animals into the hunter-gatherer societies of the Neolithic was contact with shepherds infiltrating new grazing areas from the agricultural zones of the northern Negev and the southern Mediterranean zone.

Second, evidence for human presence in periods previously undocumented for the Negev Highlands constitutes a major discovery, tying into the debate on the archaeological visibility of nomadic societies (e.g., Finkelstein and Perevoletsy 1990, Rosen 1992). The gaps
in the archaeological record of the Negev and Sinai have been interpreted alternatively as evidence of significant demographic decline (Rosen 1992) or nomadization, effecting a decrease in archaeological visibility (Finkelstein and Perevoletsy 1990). The archaeological documentation of grazing shelters attributable to periods for which no other sites have been found reflects human presence but of a fundamentally different order from that of other periods. Thus not only is archaeology able to document the traces of shepherds and their herds but the contrast between this pattern of presence and those of periods with campsites and base camps is indicative of significant demographic variation.

The demographic issue in the Negev Highlands is not a question of mere presence or absence but one of rise and decline. “No one will dispute that an occasional shepherd may have wandered through the region with a flock” (Rosen 1992:82). The materials presented here suggest that some periods may be characterized as a reversion to grazing zone—in essence, demographic decline. This is not nomadization but tribal shift, perhaps accompanied by contraction. The key point is that analysis of rockshelter sediments—archaeological sites by any definition—provides evidence for the most ephemeral of human occupation. Even the lone shepherd with a flock of several dozen sheep/goat leaves remains identifiable and analyzable to archaeology once we learn how and where to look.

Finally, it is important to recognize that analysis does not end with presence/absence of dated remains. The dung horizons described here preserve crucial evidence of paleoenvironment and climate from which we can both infer human behaviors such as seasonality, flock composition and health, and other patterns of behavior and reconstruct the ancient environments of the region. These analyses are currently in progress, and they will play an essential role in our understanding of human presence in the desert.

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Cooperation, Games, and Ecological Feedback: Some Insights from Bali

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For centuries Balinese rice farmers have been engaged in cooperative agricultural practices [Christie 1992; Scarborough, Schoenfelder, and Lansing 1999, 2000]. This remarkable achievement in sustainable agriculture is surprising given water supply conditions that would normally result in a rapid breakdown of cooperation and the absence of any centralized control mechanisms. An important cultural element of this system includes networks of water temples that help to coordinate farming practices [Geertz 1980, Lansing 1991]. Here we develop and test a simple game-theoretic model that links important features of the human and ecological systems and provides an explanation for the emergence of cooperative farming practices in a decentralized system with severe externalities and the coordinating role of the water temple system.

To foreshadow the results, we find that the typical breakdowns in cooperation one would expect to arise as upstream farmers ignore the water needs of downstream farmers are mitigated by the threat of crop pests. Simultaneous fallow periods can serve as an effective pest control strategy. Thus, upstream farmers may have an incentive to cooperate by sharing water with downstream farmers so as to minimize pest damage. Depending on the ecological links among the various fields, coordinated planting may arise and create the need for an external coordination device—a role easily filled by the observed system of water temples. We conjecture that the specific patterns and control structure of the temples broadly correspond to the coordination needs dictated by the various ecological links inherent in the ecosystem. One unusual implication of the model is that, under some circumstances, increasing the level of pest damage in the ecosystem can actually increase aggregate agricultural output.

BACKGROUND

In Bali, rice is grown in paddy fields fed by elaborate irrigation systems dependent on seasonal rivers and groundwater flows. Gravity-fed irrigation works route the water to the distant fields, creating a highly interdependent system that is physically fragile.

In general, irrigation demands are highest at the start of a new planting cycle because the dry fields must first be saturated with water. The flooding and draining of blocks of terraces has important effects on pests (including insects, rodents, and bacterial and viral diseases). The issue of pests is not a recent development—traditional Balinese lontar manuscripts such as the Dharma Pumaculan have references to hama merana (rice pests), and both Balinese and Dutch colonial sources refer to devastating plagues of rats in the paddy fields [Korn n.d.]. If farmers with adjacent fields can synchronize their cropping patterns to create a uniform fallow period over a sufficiently large area, rice pests are temporarily deprived of their habitat and their populations can be sharply reduced. Field data indicate that synchronized harvests result in pest losses of around 1% compared with losses upwards of 50% during continual cropping. How large an area must be fallow and for how long depends on specific pest characteristics [Widiarta et al. 1990, Aryawan et al. 1993, Holt and Chancellor 1996, Latham 1999]. Of course, if too many farmers follow identical cropping patterns in an effort to control pests, then peak water demands will coincide. Often there is insufficient water to meet the full needs of all farmers in such a case.

Paralleling the physical system of terraces and irrigation works, the Balinese have constructed intricate networks of shrines and temples dedicated to agricultural deities and the Goddess of the Lake. These temples de facto provide farmers with a way to coordinate cropping patterns and the phases of agricultural labor [Lansing 1991].

A MODEL

To gain insight into the above system we propose a very simple game-theoretic model.2 By design, we assume a trivial ecological structure and rely on some simple game-theoretic solution concepts; nevertheless, the resulting model is surprisingly insightful. At the outset we recognize that a variety of extensions are available, but

1. Lansing’s fieldwork on Bali was carried out under the auspices of the Lembaga Ilmu Pengetahuan Indonesia and the Bali Pene-litian dan Pengkajian Teknologi Pertanian [Denpasar, Bali] with financial support from the National Science Foundation. Balinese colleagues Alit Artha Wiguna, Sang Putu Kaler Surata, Gusti Nyoman Penath, and Gusti Ngurah Aryawan also made key contributions to various phases of this research program. Miller’s work was supported by core funding from the Santa Fe Institute and Carnegie Mellon University. We are grateful to the Santa Fe Institute for initiating the collaboration.

2. Ostrom [1996] relies on a model of similar spirit to consider collective issues that arise from upstream/downstream water externalities on Nepalese canals.
we conjecture that such additions will not fundamentally alter our conclusions.

Suppose that there are only two rice farmers, one upstream from the other. We allow the upstream farmer to have first claim on any water in the system. To simplify matters, suppose that farmers must choose one of two possible dates on which to plant their crops, \( A \) or \( B \). We assume that the water supply is adequate to accommodate the needs of one farmer during any given period but insufficient if both decide to plant simultaneously. Let \( \delta(0 < \delta < 1) \) give the crop loss due to reduced water inputs experienced by the downstream farmer if he plants at the same time as the upstream farmer.

If the farmers do not plant simultaneously, we assume that both fields will suffer damage due to pests’ being able to migrate back and forth during the growing cycles. Let \( \rho(0 < \rho < 1) \) give the crop loss due to pest migration between the fields under these conditions (we assume that there is no such damage if the crops are planted simultaneously). Given the above, the payoff matrix (numerated in crop output, with the payoff to harvesting an unencumbered field normalized to one) of the associated game is given in table 1.

The Nash (1950) equilibria of this game provide a variety of insights. The game always has a single, mixed-strategy Nash equilibrium at which the two players randomize with equal weight over the two starting times. The expected aggregate crop yield from the mixed strategy is \( 2 - \delta/2 - \rho \). Two pure-strategy equilibria (either both planting at time \( A \) or both planting at time \( B \)) arise when \( \delta \leq \rho \). Thus, when \( \delta \leq \rho \), the game can take the form of a simple coordination game in which the two players would like to plant at the same time. In either of the coordinated equilibria, the aggregate production is equal to \( 2 - \delta \). The coordinated outcome will yield a greater aggregate harvest than the mixed-strategy outcome when \( \rho > \delta/2 \). This holds because pest damage is borne by both farmers while water damage impacts only the downstream farmer; thus aggregate yields increase by coordinating when pest damage is at least half as bad as water damage.

Figure 1 summarizes these results. Parameter values below the 45° line can support only the mixed-strategy equilibrium while those above this line can, in addition, support the two pure-strategy equilibria. In terms of aggregate crop output, either of the pure-strategy equilibria results in greater output than the mixed-strategy equilibrium for all parameters above the dashed line. In particular, for all parameter values in the region between the dashed and 45° lines, such as point \( a \), aggregate output would be greater at either of the pure-strategy equilibria even though only the mixed strategy is supported. This leads to a rather counterintuitive implication: for any such point we could potentially improve the aggregate crop output by increasing the damage done by pests (that is, by increasing the value of \( \rho \)). By increasing pest damage under such circumstances, we can move the system into a regime in which coordination becomes a viable strategy, and since pest damage is fully mitigated under coordination, aggregate crop output increases.

Intuitively, the model’s logic is simple. There are two important externalities in the system: water damage \( [\delta] \) imposed by the upstream farmer on the downstream farmer and pest damage \( [\rho] \) imposed by both farmers on each other by staggered cropping. The upstream farmer is not impacted by water scarcity and therefore always has an incentive to minimize pest damage by simultaneous cropping. The downstream farmer faces either water scarcity [under simultaneous cropping] or pest damage [under staggered cropping] and therefore will choose the lesser of two evils. If pest losses are low, the downstream farmer wants to stagger cropping because of water considerations while the upstream farmer wants to plant simultaneously to avoid pest damage, and a mixed strategy ensues. If, however, pest losses are high, both farmers have an incentive to coordinate on one of the two possible simultaneous cropping patterns.

Thus, if pests are bad enough (that is, if \( \rho \geq \delta \)), then a coordinated solution emerges with both farmers receiving higher individual crop yields than they would expect under the mixed-strategy outcome. Given that the two resulting pure-strategy equilibria yield identical outcomes, both of which are better than the mixed-strategy outcome, there is an important role for an external coordination device—such as the water temple system—

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**Table 1**

<table>
<thead>
<tr>
<th>Payoffs for the Game</th>
<th>( A_A )</th>
<th>( B_B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_A )</td>
<td>( 1,1-\delta )</td>
<td>( 1-\rho,1-\delta )</td>
</tr>
<tr>
<td>( B_B )</td>
<td>( 1-\rho,1-\rho )</td>
<td>( 1,1-\delta )</td>
</tr>
</tbody>
</table>

**Figure 1.** Game equilibria.
for determining which of the two equilibria to play. Such
an entity does not require any formal enforcement power
to remain credible, as it is in the individual interest of
the farmers to follow whatever edict they collectively
choose to impose upon themselves in the water temple
(formally, this is known as a coordinated equilibrium).

As we have said, there is also a range of parameters
under which the aggregate yield is likely to improve if
more pest damage occurs [when \( \delta > \rho > \delta/2 \)]. In this range
of \( \rho \), either of the coordinated outcomes has higher ag-
gregate crop yields than the mixed-strategy outcome, but
only the mixed-strategy equilibrium is supported. Under
such circumstances, if we increase \( \rho \) to \( \rho' \) (such that \( \rho' > \delta \)), the two pure-strategy equilibria are supported and
aggregate output can be increased if one of them is adopted.3 When crops are staggered the aggregate yield falls because of pest damage to both fields. Nevertheless, the downstream farmer has no incentive to incorporate the pest damage to the upstream field in his decision calculus and may therefore prefer staggered cropping even though this lowers aggregate yield. As pest damage increases, the downstream farmer will eventually prefer the water damage of simultaneous cropping to the pest damage of staggered cropping, thus eliminating the pest damage to both fields. Although the aggregate yield will increase, the downstream farmer is worse-off under the higher pest conditions, since the initial level of pest dam-
age was such that this farmer would have preferred to incur pest damage rather than to accept the water dam-
age inherent in the coordinated outcome.

There is another potential path to improving aggregate
crop output when the parameters are such that the down-
stream farmer would prefer not to coordinate. Suppose
that the crop damage due to water [\( \delta \)] can be shared be-
tween the two farmers4 if, the upstream farmer takes
less than the full amount of water [and, in so doing, loses
some crop] and passes it on so that the downstream
farmer can experience lower crop losses. It can be shown
that there is some damage-sharing arrangement in which
both farmers will be willing to coordinate cropping for
any parameters in the range between the 45° and the
dashed line in figure 1. Moreover, as the parameters
move from the 45° line toward the dashed line, the up-
stream farmer will be forced to provide a more equal
distribution of the loss—that is, the water will need to
be more evenly shared between the two farmers—to
make the arrangement work. Although this model is in-
tentionally simplified, it appears to be robust to a variety
of changes. For example, the introduction of higher-yielding crops can be modeled by multiplying all of the
payoffs by a constant; such transformations have no im-
3. This result requires that increased pest damage not also impact
the crops under simultaneous cropping. Empirically it appears that
almost all pest damage is mitigated by simultaneous cropping.
4. More formally, we assume that the damage can be divided lin-
early between the two farmers, with the upstream farmer experi-
encing \( \alpha \delta \) and the downstream farmer receiving \( (1 - \alpha)\delta \) damage for
\( \alpha \in (0, 1] \).
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impact on the analysis.5 Instead of simultaneous choices, we
could allow one farmer to move first in the game. In
the case in which the farmers’ incentives differed, the
outcome of the game would depend on who moved first;
if they both wanted to coordinate, then the first move
could serve as a coordination mechanism.

In the model we also assumed that there were just two
players: an upstream and a downstream farmer. In Bali,
typically each such “player” is in reality composed of a
group of farmers known as a subak. Thus, our model
assumes that each subak will act as a single entity. This
assumption could be violated if, say, free riding by in-
dividual farmers destroyed its ability to act as a unified
entity. While more explicit models of subak decision
making are of interest, there are some key factors in Bali
which tend to enforce subak cohesion. In particular,
given their proximity and low mobility, individuals
within a subak have very long-term interactions with
one another in an environment in which behavior is eas-
ily observed by others. In such a world, the long shadow
of the future, multiple ties, and easily available infor-
mation tend to promote very high levels of cooperation.
Indeed, it is said that “the voice of the subak is the
voice of God.”

Finally, we could also incorporate more realistic eco-
logical considerations into the theory, and below we em-
ploy a computational model of the system with such
assumptions. Even in these more advanced models, the
basic insights gleaned from the simple model above hold.

FURTHER EVIDENCE FOR THE MODEL

The model developed above suggests a basis for the de-
centralized, self-organizing aspects of Balinese rice ag-
riculture uncovered by Korn (1932), Geertz (1980), and
Lansing (1991). It suggests that, even in the presence of
a severe water externality, farmers should be willing to
coordinate the simultaneous planting of crops to miti-
gate the potential of pest damage. Moreover, it points to
the need for some type of institutional arrangement,
such as the water temples, to facilitate coordination.
Such institutions need no formal enforcement power
[such as the threat of force or ostracism] because each
farmer has an incentive to seek and follow whatever ad-
vice is given.

Below we offer some additional support for the model.
We show how a natural experiment, the mandated year-
round cropping of high-yielding varieties of rice that de-
stroyed the coordination in the system, resulted in an
outbreak of pests, lowered aggregate output, and even-
tually a resumption of coordinated farming. Through the
use of a computational model developed separately, we
explore the consequences of extending the model to mu-
tiple players in a more ecologically realistic framework
and show how reducing the damage due to pests can
cause systemwide coordination to break down. Finally,
we use a field survey to demonstrate that the strategic concerns of upstream farmers differ in predictable ways from those of downstream farmers.

A natural experiment. The history of Bali offers an important natural experiment. The development in the early 1970s of new, high-yielding varieties of rice prompted the Indonesian government to undertake a massive redirection of agricultural policy. By 1977, 70% of rice terraces in south-central Bali were planted with the new varieties of rice, and the government mandated continuous cropping. This led to the abandonment of the temple system of irrigation control and thus rendered the previous coordination mechanism ineffective. Soon district agricultural offices began to report chaos in water scheduling and explosions of pest populations (Lansing 1991). By the mid-1980s the importance of the water temple system—previously noted in official reports only as a Balinese “rice cult”—was recognized by government officials (Lansing et al. 2001). The harvest losses caused by this breakdown of coordination provide further support for the importance of coordination mechanisms.

An artificial experiment. Another test of our theoretical ideas relies on the ecological model of Lansing and Kremer (1993; Lansing, Kremer, and Smuts 1998). This model captures major hydrological and biological features of 172 subaks relying on the Oos and Petanu Rivers in the region of Gianyar (fig. 2). The amount of water flowing at any point in the rivers and irrigation systems is determined by the seasonal patterns of rainfall and groundwater flow, irrigation diversions, and crop use. An ecologically realistic model governs the growth of crops (either rice or vegetables) and the population dynamics of pests. The correlation between predicted and observed crop yields for 1989 was 0.90.

The behavior of each subak in the model follows a simple adaptive rule. At the end of each “year” of the simulation, every subak compares its harvest with that of its four closest neighbors. If any of the neighboring subaks have higher yields, then the target subak copies the cropping pattern of its [best] neighbor for the forthcoming year. The model continues in this manner until most subaks reach a local optimum. Experiments with the above model indicate that the system quickly settles down to a stable pattern of cropping behavior. Over many hundreds of simulations, the behavior of each subak stabilized within ten model years (assuming realistic parameter values). Moreover, these patterns closely resembled the actual cropping patterns observed under the current water temple system. To test our theoretical ideas, we can manipulate the pest parameter and see if the resulting patterns of coordination and agricultural output are consistent with our predictions.

Figure 3 represents the crop coordination implied by the ecological model as a function of the virulence of pests. Each panel shows the ending state of a single trial of the model after ten years of simulated time. All three panels used identical parameters except for the level of pest damage [normal rainfall and groundwater flows, double cropping of Balinese cicih rice, and random crop timing in the initial year]. Pest virulence was either low, current, or high, where “current” reflects parameters consistent with present-day ecological conditions. Under low pest damage we see negligible coordination. As pest damage increases to parameters that reflect the current situation, we see large blocks of coordinated cropping emerging along the tributaries. Finally, as pest damage increases even more, there is a slight refinement in coordination, though most of the available gains have already been exploited.

This artificial experiment also predicts that as cooperation spreads, average rice harvests will increase throughout the watershed as pests and water are brought under effective control. Such increases in harvests may, however, contain the seeds for conflict. In particular, behavioral ecologists have suggested that envy stemming from a disparity in benefits may threaten cooperation. Thus if the results of cooperative arrangements are associated with a perceptible variation in the harvests envy may hamper cooperative arrangements. However, we find that as cooperation spreads, subaks obtain nearly identical yields which are better than any of the yields obtained prior to cooperation. These results were explored in a survey of 40 farmers in the Petanu watershed,
in which 97% agreed that their own harvests were about the same as those of the other farmers in their subak.7

**Strategic concerns.** A final test is to see whether the strategic concerns of the farmers in the system coincide with those in the model. Given the nature of the two externalities, upstream farmers should focus their strategic considerations on pest damage while downstream farmers should be more concerned about water scarcity. A field survey conducted in 1998 in ten subaks provides some useful data about the concerns of the farmers. In each subak, a stratified random sample of 15 farmers was selected, with 5 farmers each drawn from the upstream, middle, and downstream parts of the subak. Each farmer was asked, “Which problem is worse, damage from pests or irrigation water shortages?”

The results of the survey, stratified by farmers’ relative locations in their subak, are summarized in figure 4. The upstream farmers in any given subak tend to be concerned about pests and water damage at roughly equal levels. However, farmers in the middle or downstream parts of the subaks are almost exclusively concerned about water shortages. Thus there appear to be strategic concerns within subaks that align well with the assumptions of the model. Given that there are within-subak mechanisms that should promote coordination, we would expect to see a stronger separation of concerns if we analyzed the data at the subak level. Of the ten subaks in the sample, six can be paired into direct upstream/downstream neighbors, in each pair of which one obtains most of its water from the other. In figure 5 we summarize the results of the survey of this subsample aggregated by subak location, which reflect the expected strategic concerns.

Some additional support for the model comes from videotaped records of monthly inter-subak meetings. We find that the perceived threat of pest invasion appears to be strongly related to the willingness of the heads of upstream subaks to synchronize cropping. In years of high pest damage, more synchronization is observed, while in years of light rains, greater fragmentation ensues, consistent with the predictions of the model (Lansing n.d.).
The Balinese rice farming system provides an opportunity to combine anthropology with formal modeling to the benefit of both. It is rare to have such rich ecological and social data with which to inform and test game-theoretic ideas. Moreover, the modeling suggests a number of insights that may help explain some of the details uncovered by the fieldwork. While we do not wish to deny the role of more complex cultural factors in promoting cooperation, we suspect that the challenge is to place such factors in the context of the ecological trade-offs highlighted by the model.

**Fig. 5.** Survey responses about major concerns of farmers stratified by subak location for a subsample of six paired subaks (N = 90).

**Conclusions**

The cooperation that sustains the Balinese rice farming system is truly remarkable. Without centralized control, farmers have created a coordinated system that allows productive farming in an ecosystem that is rife with water scarcity and the threat of disease and pests. The game-theoretic model we have developed provides a compact explanation for many of the most salient features of the system. While externalities caused by either water scarcity or pests would, in isolation, be expected to imply a serious failure, the ecology of the rice farming system links these two externalities in such a way that cooperation can emerge. Depending on the underlying ecological parameters in the system, there are regimes in which the farmers would like to coordinate their cropping patterns (in particular, have identical fallow periods) so as to control pest populations. There are other regimes in which coordination is not an equilibrium, even though coordinated farming would result in greater aggregate crop output. We identify at least two indirect mechanisms by which the system can escape from such a trap. The first is for upstream farmers to share their water with downstream farmers, and we find that under many circumstances both parties are willing to engage in such bargains. The second is for increases in pest damage to drive the system into a coordinated equilibrium enhancing aggregate output.

Whenever the system is such that the farmers want to coordinate their activities, there is a need for some mechanism to facilitate the coordination. We suggest that the observed system of Balinese water temples fills such a role (of course, the temples have many other functions as well). Even without any direct enforcement power, the value of a centralized coordination device would give such an institution legitimacy.

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The Emergence of Social Learning in a Temporally Changing Environment: A Theoretical Model

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The behavior of a biological organism is a complex process involving the expression of relevant information possessed by that organism. For example, as we write these words, we are presumably accessing learned knowledge stored in our brains that we believe applies to the problem we hope to solve. At the risk of oversimplification (Gould and Marler 1987), it is possible to classify behaviors in terms of the three distinct ways in which this information can be obtained (Cavalli-Sforza and Feldman 1983a, Boyd and Richerson 1985, Laland, Odling-Smee, and Feldman 2000, Henrich and McElreath 2003, Alvard 2003). This trichotomous classification labels behavior as “innate,” “socially learned,” or “individually learned.”

A behavior is innate when it entails the direct expression of information encoded in the genes, which are inherited from the parents via the germ cells. Social learning denotes the transfer of information between socially interacting individuals, as a result of which the behavior exhibited by a “model” is adopted by an “observer” (Galef 1988, Whiten and Ham 1992, Heyes 1993). The rubric covers teaching, imitation (goal-directed copying of an action pattern), local enhancement (attention drawn to a particular object by the behavior of another, leading to independent discovery of that behavior), and various other psychological processes. Finally, individual learning refers to learning that occurs independently of any social influences. Examples are trial-and-error and insight.

Social learning is of interest to anthropologists because it is the process that supports cultural inheritance (Cavalli-Sforza and Feldman 1981, Durham 1991). As noted above, social learning is a generic term describing many different processes. Although social learning is exhibited by a wide variety of animals, there is much debate as to whether any nonhuman species, in particular the chimpanzee, is capable of teaching and imitation (Galef 1992, Tomasello 1994, Boesch 2003). Galef (1992) and Tomasello (1994) argue that teaching and imitation are limited to humans, which is why human culture differs quantitatively and qualitatively from animal “cultures.” Clearly, culture has undergone much elaboration in hominids since their divergence from the chimpanzee lineage and particularly within the past 50,000 years, but it is difficult to identify the cause(s) [Laland, Odling-Smee, and Feldman 2000]. We do not seek to contribute to this discussion. Rather, our interest centers on the conditions that might favor the evolution of social learning in its earliest phases.

The utility of social learning [and cultural inheritance] may seem obvious, and the reader may wonder why the question of its origin(s) is raised at all. In fact, although numerous accounts have appeared in the literature, there were few serious attempts to come to grips with the problem qualitatively until the early studies by Cavalli-Sforza and Feldman (1983a, b) and Boyd and Richerson (1985) [see also Feldman and Cavalli-Sforza 1976]. Even Lumsden and Wilson (1981:330) in their seminal work explain the advent of social learning as “the cosmic good fortune of [hominids’] being in the right place at the right time.”

However, the advantages of social learning are not so clear as to make the question of its origin(s) uninteresting. Two theoretical results obtained by Cavalli-Sforza and Feldman (1983a, b) are indicative of the difficulties. First, if both genetic and cultural determination of a selectively favored trait are possible, the former will usually prevail, at least in a constant environment (Cavalli-Sforza and Feldman 1983a). Second, when social learning occurs among a small minority of the population, it spreads slowly unless, for example, it occurs between relatives (Cavalli-Sforza and Feldman 1983b).

The model of Cavalli-Sforza and Feldman (1983b) has been extended by Aoki and Feldman (1987, 1989), Aoki (1990), and Takahashi and Aoki (1995). Cavalli-Sforza and Feldman (1983b) define a “communicator” as an organism with the genetically determined ability to acquire and pass on a socially learned adaptive behavior, whereas a “noncommunicator” is unable to do either. Communicators are more likely to spread at the expense of noncommunicators if social learning occurs within families. A “natural” way is for offspring to model their behavior on that of their parent(s), a form of social learning that has been called “vertical transmission” [Cavalli-Sforza and Feldman 1981].
Typically in mammals only the mother provides parental care. Modern humans are exceptional in that the father often participates, and a recent analysis of sexual dimorphism in *Australopithecus afarensis* suggests the antiquity of monogamy (Reno et al. 2003). When just one parent is available as a possible model for the offspring, communicators can spread through the population only if the socially transmitted behavior confers at least a twofold advantage on the communicators that acquire it (Aoki and Feldman 1987, 1989). In contrast, with both parents present a small advantage may suffice (Aoki 1990). Hence, it is possible that the human capacity for social learning, with its heavy reliance on vertical transmission (Hewlett and Cavalli-Sforza 1986, Guglielmino et al. 1995), evolved in the context of the monogamous family (Takahasi and Aoki 1995). These results have been obtained assuming environmental constancy.

Boyd and Richerson (1985) explicitly incorporate temporal or spatial variation of the environment. In their model of “guided variation,” organisms use a mixed strategy of social and individual learning. Guided variation entails the initial acquisition by social learning of a behavioral predisposition which is then modified by individual learning before being expressed as mature behavior. The proportions of social and individual learning evolve to an equilibrium at which dependence on social learning will be greater when environmental predictability is higher.

These researchers also ask when it is better to rely on social learning to acquire the initial behavioral predisposition than to inherit it genetically. Given a temporarily fluctuating environment that is autocorrelated—autocorrelation being a measure of stability across generations—they find that social learning is favored when this “autocorrelation is high, but not too high. . . . At very high autocorrelations, environments become so slowly changing that genes can track perfectly well, and the advantage of social learning disappears” (Richerson and Boyd 2000:8).

The approach taken by Boyd and Richerson (1985, 1988) is realistic in recognizing the facultative nature of individual and social learning—most organisms capable of learning use both strategies—but the price of this realism is lack of amenability to detailed mathematical treatment (but see Feldman, Aoki, and Kumm 1996). Rogers (1988) proposes a much simpler model of competition between obligate individual and social learners in a temporally variable environment. His assumptions, similar in spirit to those made by Boyd and Richerson (1985), are as follows: The environment may change between generations. There is an optimal behavior appropriate to each environmental state. Individual learners achieve this optimal behavior on their own but suffer a fitness cost due to errors made in learning. Social learners copy an organism of the parental generation chosen at random [oblique transmission (Cavalli-Sforza and Feldman 1981)] at a direct cost that is smaller but run the risk of copying an inappropriate behavior. (The term “copy” is used broadly to include all means by which an accurate transfer of information may occur.) Since only the individual learners can accurately track the changing environment—the social learners are parasitic on the individual learners—this risk increases as the frequency of individual learners decreases [or, equivalently, the frequency of social learners increases]. Hence we intuitively expect that the fitnesses of individual and social learners may be equal at some intermediate frequency and that this should define a polymorphic equilibrium. Feldman, Aoki, and Kumm (1996) rigorously reformulate the Rogers (1988) model for both periodically and randomly changing environments. Their analysis confirms the prediction (Rogers 1988) that social learners will be eliminated if the environment changes too often. Social learners can be maintained in the population if the environment is sufficiently constant and at higher frequency the greater is this stability.

Recent reviews of the factors contributing to the emergence of social learning emphasize the role played by a changing environment (Laland, Odling-Smee, and Feldman 2000, Richerson and Boyd 2000, Alvard 2003, Henrich and McElreath 2003). A consensus has been reached among these writers on the “strategy” appropriate to any given degree of environmental stability: individual learning, social learning [from the parental generation], and innate determination of behavior are favored by natural selection when environmental changes occur at short, intermediate, and long generation intervals, respectively. This proposal is quite reasonable in view of the results described above (Boyd and Richerson 1985, 1988; Rogers 1988; Feldman, Aoki, and Kumm 1996). However, the obvious study has not yet been done of simultaneously comparing individual learners, social learners, and organisms behaving innately when they are in direct competition with each other.

The purpose of this paper is to fill this theoretical lacuna. After extending the model of Feldman, Aoki, and Kumm (1996) to include innate behavior, we show by way of numerical examples that this consensus view is basically true for both periodically and randomly changing environments, provided that certain conditions are met. However, we also find significant differences between the predictions of the periodic-environmental-change model and the random-environmental-change model. In addition, our numerical work suggests that social learners may lack the opportunity to copy a genetically inherited behavior and therefore such a behavior is not likely to become part of a species’s cultural repertoire unless “reinvented” by individual learners.

**Environmental Changes and Phenogenotypes**

Feldman, Aoki, and Kumm (1996) assume a population of haploid asexual organisms with two genetically determined strategies, social and individual learning. We extend their model to include innate behavior. Thus, in our model a tri-allelic “strategy” locus determines whether an organism is an “innate,” a social learner, or an individual learner. Social learners acquire their behavior—or, rather, the information required to express
the behavior—from an organism of the parental generation. Their behavior will be adaptive or maladaptive depending on whether the information obtained is appropriate to their current environmental state. Individual learners collect information directly from the environment and always achieve the adaptive behavior on their own. The information needed for innate behavior must be stored genetically. Accordingly, we posit an “innate information” locus with two classes of alleles, the “resident” alleles producing behavior that is adapted to the current environmental state and the “mutant” alleles producing maladaptive behavior. When an innate carries a resident allele at the innate information locus, its behavior is adaptive. Carrying a mutant allele results in maladaptive behavior. Each of the two classes of alleles comprises many selectively neutral variants. Hence, there may be a variety of adaptive behaviors, which by assumption are equally adaptive (i.e., have the same fitness), and similarly a variety of maladaptive behaviors. A small subset amounting to a fraction \( r \) of each class possesses the special property of being adaptive when the environment changes. These variants can be regarded as “preadapted” alleles awaiting environmental change. The innate information locus is not expressed in individual and social learners.

By assumption, individual learners always behave appropriately for the given environmental state, but social learners and innates can get it either right or wrong. Therefore our model distinguishes five phenogenotypes (genotype-phenotype combinations [Feldman and Cavalli-Sforza 1984]): GC [genetic correct, i.e., innate with resident allele], GW [genetic wrong, i.e., innate with mutant allele], SLC [social learner correct], SLW [social learner wrong], and IL [individual learner]. The five phenogenotypes, their frequencies among reproductive adults, and their fitnesses are summarized in table 1. The fitnesses are relative viabilities and are assigned to the five phenogenotypes in the following way: There is a baseline fitness of 1 for adaptive behavior. Maladaptive behavior causes the fitness to be reduced by \( s \). Social learners bear a direct cost of developing and maintaining a nervous system supportive of learning, which is translated into a fitness loss \( d \). Individual learners suffer a similar—though not necessarily equivalent—direct cost and are also adversely affected by mistakes made before the mature behavior is realized; the total penalty is \( c \).

In the periodic-environmental-change model, the environment changes every \( l \) generations. In other words, one (postchange) generation experiences a different environmental state from the previous generation, and \( l-1 \) subsequent generations experience the same state as the previous generation. Larger values of \( l \) imply more environmental stability. Rogers (1988) posits two states between which the environment alternates. However, the number of possible environmental states is likely to be large. As an idealization this number is assumed to be infinite, so that when the environment changes it never reverts to an earlier state (Feldman, Aoki, and Kumm 1996). None of the preexisting behaviors can be adaptive after an environmental change. The infinite-state model may be a realistic representation of long-term environmental change, particularly if the environment is assumed to include other evolving species.

### Evolutionary Dynamics with Periodic Environmental Changes

Given that the state of the environment after a change is unprecedented, the innates will be rapidly eliminated from the population unless variant alleles segregate at the innate information locus that “anticipate” the environmental change. As described above, we assume that a small fraction, \( r \), of all alleles at the innate information locus have the serendipitous property of being “preadapted.” They become resident alleles when the environment changes regardless of their status before the change. The remaining fraction, \( 1-r \), of all alleles then become mutants.

The behavior of an innate in our model is the result of an interaction between the allele it carries and the environment it experiences. In particular, an innate carrying a preadapted allele behaves differently in the pre- and postchange generations. Consistent with our basic premise—that none of the preexisting behaviors can be adaptive after an environmental change—we assume that its behavior in the prechange generation is maladaptive in the postchange generation. This implies that a social learner cannot acquire correct behavior by copying an innate with a preadapted allele when the environment changes.

The life-cycle events are mutation, asexual reproduction, learning, and natural selection, in that order. The recursions relating the frequencies of the five phenogenotypes in the offspring generation, indicated by primes, to those in the parental generation can be written as follows: First, when the environment changes between generations they are

\[
\begin{align*}
u' &= \rho(1+\rho) / V, \\
v' &= (1-s)(1-\rho) / (1-\rho + V), \\
x' &= 0, \\
y' &= (1-s-d) / (x+y), \\
z' &= (1-c)z / V, \\
\end{align*}
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where \( V = [\rho + (1-s)(1-\rho)(1+\rho) + (1-s-d)(x+y) + \ldots] \) and

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Figure 1 illustrates the dependence on period length, \( l \). On the horizontal axis, \( l \) is given on a log scale. On the vertical axis are plotted the frequencies, averaged over one period at equilibrium, of inmates (GC and GW combined, frequency \( u + v \)), social learners (SLC and IL, respectively; they define the surviving fractions of each phenogenotype after viability selection. Finally, normalizing by \( W \) gives the frequencies among reproductive adults of the offspring generation.

The recursions with environmental change \( \{1\} \) can be obtained by modifying the above argument. Among newborns the frequencies of GC and GW are \( \rho(u + v) \) and \( (1-\rho)(u + v) \), respectively (lines 1 and 2). No members of the parental generation are behaving adaptively as viewed by members of the offspring generation, and therefore the fractions of naïve social learners that become SLC and SLW are \( 0 \) and \( 1 \), respectively (lines 3 and 4). IL are unaffected by environmental change, and line 5 remains the same.

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SLW combined, frequency $x + y$), and individual learners (IL, frequency $z$). The values of the other parameters are $s = 0.1$, $c = 0.02$, $d = 0.01$, and $p = 0.000001$. Three properties of the plots are worth noting. First, individual learners, social learners, and innates dominate (i.e., reach high frequencies) at short, intermediate, and long periodicities, respectively. This result clearly supports the consensus view [Laland, Odling-Smee, and Feldman 2000, Richerson and Boyd 2000, Alvard 2003, Henrich and McElreath 2003] Second, a critical period length, $I^*$, exists such that innates are absent when $I \leq I^*$ and individual and social learners are both absent when $I > I^*$. In this particular example we find that $I^* = 683$ generations. Third, social learners always coexist with individual learners, on whom they are parasitic, and their frequency increases continuously as period length increases up to the threshold $I^*$. Together the second and third properties imply that at equilibrium social learners do not acquire their behavior by copying the innates. Caution is required in generalizing from the results of numerical work, but the features noted above apparently hold whenever $d < c < s$, as in this example. This ordering entails that the direct cost of social learning is small compared with the total cost incurred by the individual learners and both are smaller than the fitness loss due to maladaptive behavior.

**Constraints on the fitnesses**

As we have seen, the fitnesses of SLC, GW, and IL are $1 - d$, $1 - s$, and $1 - c$, respectively. If $d < c < s$, SLC has a higher fitness than either GW or IL. Hence, provided that most social learners are SLC rather than SLW and most innates are GW rather than GC, the social learners will on average “do better” than either the innates or the individual learners. Such a situation obtains at intermediate environmental periodicities—when the period is long enough for most social learners to acquire the adaptive behavior but too short for most innates to be carrying the resident allele at the innate information locus.

There are six ways in which the three quantities, $s$, $d$, and $c$, can be ordered, including the case $d < c < s$ already considered. Let us briefly indicate why social learning cannot evolve in the five remaining cases. If $s < d$, the fitness of a social learner can never exceed the fitness of an innate. Similarly, if $c < d$, the fitness of a social learner is always less than the fitness of an individual learner. Hence, if either inequality holds (i.e., if $s < d < c$, $s < c < d$, $c < s < d$, or $c < d < s$), the social learners will be eliminated. This leaves the case $d < s < c$, but then the individual learners lose in competition to the innates and as a result the social learners, parasitic on the individual learners, will also disappear. Thus, the only condition that permits the evolution of social learning is

$$d < c < s.$$  \hspace{1cm} (3)

Clearly, the statement that individual learners, social learners, and innates dominate at short, intermediate, and long periodicities, respectively, must be qualified.

**Evolutionary dynamics with random environmental changes**

We have been assuming environmental changes at regular intervals of $l$ generations. Real environments, however, do not change according to a fixed schedule even when there is an underlying periodicity; for example, this is true of the onset of the four seasons. An extreme alternative to the periodic-environmental-change model is the random-environmental-change model, which assumes that in any generation the environment changes with probability $p$. To facilitate comparison between the two models, we set $p = 1/l$. Then on average the environment will change every $l = 1/p$ generations. As before, recursions 1 apply when the environment changes and recursions 2 apply when the environment is constant. However, the iterations do not follow a fixed order, since the timing of environmental changes is random.

The model of random environmental changes was simulated numerically by generating one uniform random number, $R$, between 0 and 1 per generation. If $R < p$ (i.e., with probability $p$) recursions 1 were applied. If $R > p$ (i.e., with probability $1 - p$) recursions 2 were applied. This was continued for $100,000$ generations. The first $50,000$ generations were discarded to allow for the possibility that “equilibrium” had not been reached, and the phenogenotype frequencies were evaluated over the remaining $50,000$ generations. Since our interest is in the average tendencies rather than the results unique to each realization of the stochastic process, we ran 100 such simulations.

Figure 2 illustrates the dependence on the probability of environmental change, $p$. On the horizontal axis the reciprocal of this probability, $l = 1/p$, is given on a log scale, facilitating comparison with figure 1. On the vertical axis are plotted the frequencies of innates (GC and GW combined), social learners (SLC and SLW combined), and individual learners (IL). Each point represents an average over 100 runs for generations 50,001 through 100,000. The other parameters are as before: $s = 0.1$, $c = 0.02$, $d = 0.01$, and $p = 0.000001$. The overall picture is remarkably similar to figure 1. Thus, on average, we see that individual learners, social learners, and innates dominate when the value of $l$ is small, medium, and large, respectively.

However, we note several differences. First, there is a “boundary layer” of finite width between the regions where social learners and innates are on average dominant. The average frequencies of social learners and innates change continuously in the boundary layer, whereas in the periodic-environmental-change model a sharp transition was observed at the threshold, $l^*$. This result is attributable to the considerable variance among the 100 runs in the frequencies of social learners and innates for any value of $p$ in the boundary layer.

Second, the boundary layer is centered to the left of
$I^r$, although the deviation is small. In fact, the intersection of the curves labeled $x + y$ and $u + v$ occurs at $p = 0.00148$ corresponding to $l = 676$, whereas $I^r = 683$. However, since the boundary layer is finite in width, the upper bound on the average period for which social learning dominates is significantly smaller when the environment changes randomly (the frequency of social learners approaches 1 when $l = 465$ [fig. 2]). Since real environments do not change at regular intervals, predictions derived from deterministic models that make this assumption may be qualitatively but not quantitatively applicable.

Third, the average frequency of individual learners shows a secondary peak in the boundary layer. The maximum, 0.162, occurs at $p = 0.00149$ corresponding to $l = 670$. Once again there is considerable variance among the 100 runs in the frequency of individual learners for any value of $p$ in the boundary layer. In fact, individual learners temporarily dominate in some realizations of the stochastic process. Hence, in a randomly changing environment, individual learners may sometimes reach nonnegligible frequencies even at intermediate average period lengths.

We repeated the numerical work with other parameter sets satisfying inequality 3. The differences noted above between the periodic and the random model appear to hold in general.

**Concluding Remarks**

Building on the work of Boyd and Richerson (1985, 1988), Rogers (1988), and Feldman, Aoki, and Kumm (1996), we have shown that individual learning, social learning, and innate determination of behavior are favored by natural selection when environmental changes occur at short, intermediate, and long intervals, respectively. This prediction is qualitatively true whether the timing of the changes is deterministic or random but is subject to the constraint that the selection coefficients $c$, $c$, and $d$ must satisfy $d < c < s$ (inequality 3). Our approach differs from previous studies in that it simultaneously compares the three strategies in direct competition with each other.

The conditions favoring the evolution of social learning in its earliest phases are not excessively stringent, and therefore the wide phylogenetic distribution of primitive social learning is not a mystery (Laland and Hoppitt 2003). However, we emphasize in this regard that only the behaviors that can be “invented” by individual learning processes can be socially transmitted; social learners cannot “plagiarize” innate behavior. This is because at equilibrium social learners coexist with the individual learners but not the innates, except possibly when the environment changes randomly and the average period lies in the narrow boundary layer. Hence, the “content of culture” is limited by the capacity for individual learning as much as by the capacity for social learning.

There remains the task of testing the predictions against data on the phylogenetic distribution of social learning. Clearly, this would be a formidable undertaking. First, the relevant environmental factors would have to be identified. What exactly is changing that might make it profitable to employ a social learning strategy? Second, the timescale of these environmental changes relative to the generation length of each species would have to be determined, and we need to know whether these changes occur regularly or at random. Third, we would require estimates of the strength of natural selection acting on the three strategies. Quantitative predictions on the period length that might favor social learning cannot be made without information on the selection coefficients.

Finally, we mention one complication that cannot be ignored. Given that innate behavior was the primordial state, neither individual nor social learning could have arisen without mutation. Hence, introducing mutation among the three strategies enhances the realism of our model. When recursions 1 and 2 are appropriately modified to incorporate this assumption and then iterated with periodic environmental changes, we find that individual learners coexist with the innates when $l > l^r$. When the modified recursions are iterated with random environmental changes, we observe a significantly wider boundary layer than for the case of no mutation at the strategy locus (Wakano, Aoki, and Feldman 2004).

**References Cited**


races. Pressure from local law enforcement officials who insist on “knowing” the social race of unknowns may prompt some forensic anthropologists to designate racial affinity (provided that the sex of the individual can be determined), producing classifications that some have called “bureaucratic races.” However, the use of forensic tools to determine ancestry must assume that a given cranium is more similar to those of the ascribed population than to those of any other (e.g., Byers 2002). The fact that populations are variously defined as geographic regions, islands, countries, reproductive isolates, languages, cultures, or race categories may severely limit the reliability of such diagnoses.

Fordisc 2.0 is a computer program designed to standardize the attribution of population affinity for forensic analysis and to provide a user-friendly method for ascribing “social race” to unknowns. Social race is an approximation of biological affinity and is used as the most practical means to identify unknown individuals, regardless of their actual ancestors (Ousley and Jantz 1996).

A basic premise of the program is that the unique craniofacial form of a given population remains stable through generational time and is largely resistant to environmental factors. This premise has recently received support from a revisionist historical study claiming to have identified statistical flaws in the initial study of changes in the bodily form of immigrants (Sparks and Jantz 2002; cf. Gravlee, Bernard, and Leonard 2003). This development has strengthened the perceived efficacy of Fordisc 2.0 by suggesting that population and racial traits are constant over time and space.

The popularity of Fordisc 2.0 parallels recent public interest in forensic anthropology, the race concept, and race determination. New forensic anthropology texts present the program uncritically even when it yields determinations opposite to those derived from morphological evaluation. Hard Evidence, a forensic anthropology reader (Steadman 2003), features five articles that use Fordisc 2.0 (none of them exclusively to determine race and/or sex), and in two of them it yielded the opposite of standard morphological determinations. Forensic Osteological Analysis (Fairgrieve 1999) includes two contributions that utilize Fordisc 2.0 to [1] confirm a morphological evaluation of sex and [2] determine ancestry (this attempt proved unsuccessful). Byers’s (2002) Introduction to Forensic Anthropology embraces Fordisc 2.0 alongside the nonmetric traits traditionally used by many forensic anthropologists to define social race. The program is “highly recommended” for diagnosing race and sex in the popular Forensic Anthropology Training Manual (Burns 1999:40).

Reports of Fordisc 2.0 analyses in the primary literature are scarce, suggesting that practitioners of this program are using a tool that has not been systematically tested for validity. Fordisc 2.0 produced poor results in Ubelaker et al. (2002) study of sixteenth- and seventeenth-century Spanish crania, with half the crania being attributed to non-European/North African samples using one of its data sets, Howells’s (1973, 1995) cranial series, and less than half attributed to the white category using its other data set, the Forensic Data Bank (Ousley and Jantz 1996). Ubelaker et al. (2002) nevertheless call it “a powerful tool in forensic analysis that is routinely employed in most North American forensic laboratories” and generally support its use provided that care is taken when the samples are not represented in either of its databases (see also Ousley and Jantz 1996).

Other researchers are less convinced of Fordisc’s practical use. Fukuzawa and Maish (1997) sought to ascribe ancestry to Native Canadians without success, and Leathers, Edwards, and Armelagos (2002) and Belcher, Williams, and Armelagos (2002) found that the program failed to classify populations as expected. We used both of its data sets to identify cranial remains from an ancient Merotic Nubian population and found that it accurately classified very few of these remains.

**Materials and Methods**

Ancient Nubia, located on the upper Nile between the first and fourth cataracts, was ancient Egypt’s most powerful rival and important trade partner on the African continent (Williams 1999). From Pre-Dynastic times to the Roman conquest, Nubia and Egypt borrowed heavily from each other’s material culture and maintained substantial genetic admixture (Keita 1992, Krings et al. 1999, Williams 1999). While Brace et al. (1995) found Egyptians craniofacially distinct, they also identified a north-south gradient of craniofacial traits from the Nile Delta through Nubia to Somalia. Keita (1992) found that First Dynasty Egyptians from Abydos were similar morphometrically to those from Kerma (south of Nubia). A recent study on mtDNA suggested that modern Nubians and Egyptians are much more similar to one another than either is to southern Sudanese populations and that the divergence between the two northern populations may have occurred during the past few hundred or few thousand years (Krings et al. 1999).

We hypothesized that, using Howells’s data in Fordisc 2.0, our Nubian crania (dated 50 BCE–AD 350) would be identified as Late Period Dynastic Egypt (Twenty-sixth to Thirtieth Dynasties, 600–200 BCE), since these data correspond roughly geographically to ancient Nubia. Howells’s (1973, 1995) cranial series consists of 28 skeletal samples: Easter Island, Medieval Norse, Zalavar (medieval Hungary), Berg (Austria), Egypt (Twenty-sixth to Thirtieth Dynasties), Teita (Kenya), Dogon (Mali), Zulu and San (South Africa), Andaman Islands, Lake Alexandrina Tribes (Australia), Tasmania, Tolai (New Britain), Mokapu (Hawaii), Buriat (Siberia), Inuit (Greenland), Arikara and Santa Cruz Island (North America), Yauyos (Peru), Ainu, Hokkaido, and Kyushu (Japan), Atayal (Taiwan), Guam, Anyang and Hainan (China), Miori (Chatam Islands), and the Philippines, roughly equally divided into 50 males and 50 females for each sample. Although Fordisc 2.0 is intended to identify only unknowns represented in its control population sets, it will theoretically classify an individual to its nearest geographical neighboring population when one is available.
(Ousley and Jantz 1996). Alternatively, the Nubian material might have been classified as other African continental populations [e.g., the Teita of Kenya or the Dogon of Mali], although these scenarios are less likely because these populations are temporally distinct from ancient Meroitic Nubia and farther from Nubia than Egypt. We expected the Nubian population to cluster as a group and to be attributed to populations geographically near it.

Next, following Ubelaker, Ross, and Graver (2002) we subjected the Nubian crania to Fordisc’s Forensic Data Bank series, which includes American blacks (150 males, 125 females), American Indians (50 males, 29 females), American whites (271 males, 195 females), Chinese (79 males), Hispanics (39 males), Japanese (100 males, 100 females), and Vietnamese (51 males) [Jantz and Moore-Jansen 1988, Ousley and Jantz 1996]. We expected the program to identify the Nubian sample as black or white. We did not expect any of these crania to be classified as Chinese, Japanese, or Hispanic because of the geographic distance separating these populations from Northeast Africa. Since sex can also be ascribed using Fordisc 2.0, we conducted two tests using the Forensic Data Bank, one with sex known and the other with opposite sex known. We anticipated that the sex attributed to a given cranium would not alter the ascribed biological affinity of that individual. If populations can be readily defined as discrete multivariate clusters, as they are in Fordisc 2.0, we would predict distinct morphological patterns to be exhibited by both males and females of a given population, despite the arguably more obvious patterns of sexual dimorphism observed in human crania.

The craniofacial linear distances we used were obtained by one of us (GJA) from an archeological series of Nubian crania originating from sites opposite modern Wadi Halfa (21°57′28″ N and 31°19′10″ E) in present-day Sudan. We used 12 cranial measurements for each cranium: glabella to opisthocranion, maximum cranial breadth, bizygomatic breadth [distance between the most lateral points of the zygomatic arches], basion to bregma, nasion to basion, basion to prosthion, prosthion to alveol, minimum frontal breadth [distance between the two frontotemporale], nasion to nasopinale, nasal breadth [maximum breadth of the nasal aperture], dacency to ectoconchion, and orbital height [distance between the superior and inferior orbital margins]. Of the original 46 adult crania available, 20 crania were male, 20 female, and 6 indeterminate. Of these 46 crania, 4 individuals were excluded because they were missing three measurements, but we included 3 crania that were missing only one of the 12 measurements. Fordisc 2.0 was used to identify each of the remaining 42 crania.

The measurements were chosen on the basis of preservation of the material and the choices given by Fordisc 2.0. These same measurements have been utilized by numerous craniometric studies and have been shown to have diagnostic value [see Howells 1995 and references therein]. To ascertain whether the Nubian cranial data were comparable to the control samples in Fordisc 2.0, we compared the Nubian sample with all the African populations from Howells’s [1995] data set. Half of the traits compared between the Nubian and the Egyptian populations yielded nonsignificant differences (p > 0.05), which is greater than or equal to the number of nonsignificant differences obtained by comparing the Egyptian sample with other African populations (San, Zulu, Teita, Dogon). This suggests that the Egyptians are more similar to the Nubians than they are to any other African population.

In Fordisc 2.0, an unidentified skull is ascribed a population affinity by identifying the closest Mahalanobis distance from the unknown to the mean vector scores for each of Fordisc’s skeletal samples. Additionally, Fordisc 2.0 calculates the typicality and posterior statistical probabilities that a single cranium belongs to a specific group. Posterior probabilities (which sum to 1) ascertain the likelihood that a given cranium belongs to more than one sample, whereas typicality probabilities (from 1.0 to 0.000) identify whether a given unknown is statistically significantly different from the population ascribed by the program. Typicality probabilities of 1.0 suggest that a given cranium has values that lie exactly on the mean of one of Fordisc’s populations, whereas typicality probabilities less than 0.05 suggest that the cranium is significantly different from the population attributed by Fordisc 2.0 [Ousley and Jantz 1996, Jantz, personal communication].

RESULTS

The Howells series. Fordisc 2.0 could not effectively classify ten of the crania, and of the remainder, eight were identified as Late Period Dynastic Egyptian, six as Zalav, four as Easter Islander, three as Lake Alexandrina Tribes, and three as Norse [Medieval Norway]. Eight were not significantly different from eight separate populations: Teita, Andaman Islands, Zulu, Arikara, Santa Cruz Island, Ainu, Hokkaido, and Atayal. In no case did a nonsignificant typicality statistic exhibit a nonsignificant posterior probability, indicating that each cranium did not belong to a skeletal sample other than the one indicated by the typicality statistic. The typicality statistics were neither uniformly high nor low (table 1).

The Forensic Data Bank. Our data were analyzed twice using the Forensic Data Bank in Fordisc 2.0 to examine the degree to which specifying the sex of an individual might alter the results. When the original sex determinations (derived from associated pelvic material) were used, 14 of the crania were significantly different from the population specified by Fordisc 2.0 [typicality p < 0.05]. Of the remaining crania, 12 were identified as white, 11 as black, 3 as Japanese, 1 as Hispanic, and 1 as Native American. When the sex determination was changed to the opposite of the one identified in the orig-

1. Ousley and Jantz [1996] caution Fordisc 2.0 users to avoid classifying individuals from ethnic groups that are not represented in the database of the program. However, forensic anthropologists may not know a priori whether an isolated cranium derives from one of Fordisc’s reference samples.
inal morphological analysis, the number of crania exhibiting a typicality \( p < 0.05 \) increased to 17. Eleven of the crania (excluding those with \( p \) values \( < 0.05 \)) changed population when the sex determination was changed to its opposite (fig. 1), suggesting that Fordisc 2.0 relies heavily on the assigned sex determination in attributing population affinity. The identities assigned to the crania in this test (9 black, 7 white, 7 Hispanic, 1 Chinese, and 1 Japanese) differed most markedly from the previous analysis in that the Hispanic category increased substantially.

**Discussion**

The fact that the Nubian crania were overwhelmingly misclassified and that only eight were grouped with Late Period Dynastic Egypt may have a variety of explanations. Since there is no Meroitic Nubian sample in the program’s data sets, there may have been no specific reference sample to compare with these ancient crania. However, Howells’s populations were selected to sample the cranial variation found on the continents. If the Late Period Dynastic Egyptian crania differed greatly from the Nubian ones—and our \( t \) tests suggest that they do not—then the Nubian crania might have been classified with other geographically close populations such as the Teita or the Dogon. Alternatively, we might suspect all of the typicality probabilities to be significantly different from the populations ascribed by the program. Instead, Fordisc 2.0 classified the Nubian crania with populations over an enormous geographic range, including North and Central Europe, Easter Island, the Andaman Islands, Japan, Taiwan, South Africa, Australia, and North America. Fordisc’s treatment of X-group Nubians corroborates

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**Table 1**

*Fordisc 2.0 Results Using Howells’s Cranial Data*

<table>
<thead>
<tr>
<th>ID</th>
<th>Attributed Sex</th>
<th>Population Ascribed by Fordisc 2.0</th>
<th>Posterior ( p )</th>
<th>Typicality ( p )</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Indeterminate</td>
<td>Zalavar (Hungary)*</td>
<td>0.173</td>
<td>0.003</td>
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<tr>
<td>2</td>
<td>Male</td>
<td>Lake Alexandria Tribes (Australia)</td>
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<tr>
<td>3</td>
<td>Male</td>
<td>Lake Alexandria Tribes (Australia)</td>
<td>0.520</td>
<td>0.303</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>Late Period Dynastic Egypt*</td>
<td>0.907</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>Female</td>
<td>Norse (Norway)</td>
<td>0.326</td>
<td>0.091</td>
</tr>
<tr>
<td>6</td>
<td>Female</td>
<td>Zalavar (Hungary)</td>
<td>0.109</td>
<td>0.864</td>
</tr>
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<td>7</td>
<td>Female</td>
<td>Teita (Kenya)</td>
<td>0.233</td>
<td>0.197</td>
</tr>
<tr>
<td>8</td>
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<td>Zalavar (Hungary)</td>
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<td>0.589</td>
</tr>
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<td>Male</td>
<td>Late Period Dynastic Egypt</td>
<td>0.427</td>
<td>0.312</td>
</tr>
<tr>
<td>10</td>
<td>Female</td>
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<td>0.841</td>
<td>0.000</td>
</tr>
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<td>11</td>
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<td>Andaman Island</td>
<td>0.272</td>
<td>0.529</td>
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<tr>
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</tr>
<tr>
<td>14</td>
<td>Female</td>
<td>Easter Island*</td>
<td>0.094</td>
<td>0.000</td>
</tr>
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<td>15</td>
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<td>0.460</td>
<td>0.795</td>
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<td>16</td>
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<td>0.351</td>
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<td>Norse (Norway)</td>
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<tr>
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<td>Male</td>
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<td>0.394</td>
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<tr>
<td>20</td>
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<tr>
<td>26</td>
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<td>0.915</td>
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<td>27</td>
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<td>0.348</td>
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<td>0.349</td>
<td>0.239</td>
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<tr>
<td>29</td>
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<td>Peru*</td>
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<td>0.000</td>
</tr>
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<td>Female</td>
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<td>0.470</td>
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<tr>
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<td>0.864</td>
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<td>Late Period Dynastic Egypt*</td>
<td>0.994</td>
<td>0.003</td>
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<td>0.438</td>
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<td>0.349</td>
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<tr>
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<td>37</td>
<td>Male</td>
<td>Ainu (Japan)</td>
<td>0.348</td>
<td>0.152</td>
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<tr>
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<td>Female</td>
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<td>0.406</td>
<td>0.051</td>
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<td>39</td>
<td>Male</td>
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<td>0.443</td>
</tr>
<tr>
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<td>Indeterminate</td>
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<td>0.172</td>
</tr>
<tr>
<td>42</td>
<td>Indeterminate</td>
<td>Norse (Norway)</td>
<td>0.313</td>
<td>0.701</td>
</tr>
</tbody>
</table>

*A cranium is significantly different from the population ascribed by the program [typicality \( p < 0.05 \)].*
these results (Leathers, Edwards, and Armelagos 2002). If Fordisc 2.0 is revealing genetic admixture of Late Period Dynastic Egypt and Meroitic Nubia, then one must also consider these ancient Meroitic Nubians to be part Hungarian, part Easter Islander, part Norse, and part Australian Aborigine, with smaller contributions from the Ainu, Teita, Zulu, Santa Cruz, Andaman Islands, Arikara, Ayatal, and Hokkaido populations. In fact, all human groups are essentially heterogeneous, including the samples within Fordisc 2.0. Using $FST$ heritability tests, Relethford (1994) demonstrated that Howells’s cranial samples exhibit far more variation within than between skeletal series. There is no reason to assume that the heterogeneity of the Late Period Dynastic Egyptian population exceeds that characterizing our Nubian sample. This heterogeneity may also characterize the populations in the Forensic Data Bank; Fordisc 2.0 classified the Meroitic Nubians not as either all black or all white but as black, white, Hispanic, Chinese, Japanese, and Native American.

The fact that these groupings exist in the Forensic Data Bank of Fordisc 2.0 may stem from a specific understanding of race in America. Folk taxonomies of race are largely nation-specific because they develop from unique historical and demographic factors. For example, the fluidity and multiplicity of racial terms in Brazil corresponds to the lack of hypodescent rules (attributing one’s social race to the race of the minority parent) and miscegenation laws; an individual’s ascribed whiteness or blackness may change with respect to economic prosperity [money “whitens” (Degler 1970)]. In Trinidad, the folk separation of groups uses a much wider range of labels, to the point that full siblings may be of different “races” (Segal 1993). Attribution of race depends heavily on culturally constructed definitions of human difference.

Our results suggest to us that Fordisc 2.0 is fundamentally flawed not only because these types are culturally mediated but because statistically defined populations cannot adequately represent the biological variation that characterizes individuals within each purported group. The idea that human beings represent distinct and divisible biological types is rather recent in human history (Marks 1995), and the lines that are drawn to make distinctions are based on socioeconomic factors and historical circumstances rather than strictly on biological criteria (Armelagos 1995, Goodman 1995, Marks 1995). The type concept relies upon an “idealized” individual that describes only a minute fraction of the variation it is intended to represent. Forensic anthropology has often been called upon to substantiate typological thinking and to reinforce the type concept itself.

The idea that head type is stable through time and thus resistant to environmental factors was very popular among natural scientists from the seventeenth to the nineteenth century. Mid-twentieth-century physical anthropology sought to trace independent human lineages by associating craniofacial remains from past populations with their supposed modern counterparts [Boule and Vallois 1957, Coon 1962]. During the same period, several studies demonstrated plasticity of body type through such processes as developmental acclimatization [Baker 1969, Frisancho 1970] and migration to new areas [Shapiro 1939, Bogen 1988]. This may help to explain why European Upper Paleolithic populations do not resemble modern Europeans (van Vark 1994), why Kennewick man does not resemble modern Native Americans [van Vark, Kuizenga, and Williams 2003, contra Jantz and Owsley 2003], why American-born children of immigrants resemble their parents less than European-born children of immigrants do (Boas 1912, contra Sparks and Jantz 2002), and why Mesolithic Nubians do not resemble Meroitic Nubians (Van Gerven, Armelagos, and Rohr 1979). This reflects simply what is known about the patterns of variation in the human cranium: it is to some extent an inborn characteristic and also developmentally very sensitive to the conditions of growth. While we acknowledge that many scientists are fully aware of the problems inherent in Fordisc 2.0 and in race determination generally, our experiment provides a point of view that is rarely examined within forensic anthropology, that is, that human cranial populations are suspect as real biological units equivalent to the cultures, languages, geographic regions, and social histories they are intended to represent.

CONCLUSIONS

We argue that Fordisc 2.0, encapsulating the major skeletal markers and statistical techniques in forensic anthropology, offers little information with regard to the biological affinity of Meroitic Nubians. Given the claims of the program, we predicted that the Nubian population would cluster as a single entity and that the cluster would reflect an affinity to Late Period Dynastic Egyptians or possibly to other African continental popula-

**Fig. 1. Population ascribed using Fordisc 2.0’s Forensic Data Bank.** Left bar of each pair, original sex assignment; right bar, opposite original sex assignment.
tions. The program failed both tests. We suggest that skeletal specimens or samples cannot be accurately classified by geography or by racial affinity because of (1) the wide variation in crania of the known series that crosscuts geographic populations [polymorphism], (2) the clinal pattern of human variation, and (3) cultural and environmental factors. Even a presumably homogeneous population such as the Meroitic Nubians shows extensive variation that preclude its classification as a geographic group.

The control population sets within Fordisc 2.0 lack the distinctive morphology necessary to make this forensic application a useful tool for classifying an unknown cranium because the populations used are defined not on the basis of biology but on the basis of the variation in skeletal series or on self-assignment to folk categories that have strong sociohistorical (e.g., black, white), national [Chinese, Japanese], and linguistic (Hispanic) components. Our results suggest that the attempt to classify populations into natural geographic groups or races—as if all of these groupings were biologically equivalent—will continue to fail [Armelagos and Van Gerven 2003].

It is well known that human biological variation is principally clinal [i.e., structured as gradients] and not racial [i.e., structured as a small number of fairly discrete groups]. The possibility that skeletal material could be accurately sorted by geographic origin, at any other level than geographic extremes, is quite small. We have shown that for a temporally and geographically homogeneous East African population, the most widely used “racial” program fails to identify the skeletal material accurately.

The assignment of skeletal racial origin is based principally upon stereotypical features found most frequently in the most geographically distant populations. While this is useful in some contexts (for example, sorting skeletal material of largely West African ancestry from skeletal material of largely Western European ancestry), it fails to identify populations that originate elsewhere and misrepresents fundamental patterns of human biological diversity.

Finally, the assumption that cranial form is an immutable “racial” character is very likely to be false, given the diversity of studies of immigrants and the known effects of food preparation and masticatory stress upon cranial form. Cranial form, like other parts of the body, is a phenotype partly determined by heredity but also strongly influenced by the conditions of life.

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