Cultivation of cereals by the first farmers was not more productive than foraging

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Did foragers become farmers because cultivation of crops was simply a better way to make a living? If so, what is arguably the greatest ever revolution in human livelihoods is readily explained. To answer the question, I estimate the caloric returns per hour of labor devoted to foraging wild species and cultivating the cereals exploited by the first farmers, using data on foragers and landabundant hand-tool farmers in the ethnographic and historical record, as well as archaeological evidence. A convincing answer must account not only for the work of foraging and cultivation but also for storage, processing, and other indirect labor, and for the costs associated with the delayed nature of agricultural production and the greater exposure to risk of those whose livelihoods depended on a few cultivars rather than a larger number of wild species. Notwithstanding the considerable uncertainty to which these estimates inevitably are subject, the evidence is inconsistent with the hypothesis that the productivity of the first farmers exceeded that of early Holocene foragers. Social and demographic aspects of farming, rather than its productivity, may have been essential to its emergence and spread. Prominent among these aspects may have been the contribution of farming to population growth and to military prowess, both promoting the spread of farming as a livelihood.

labor productivity | technological change | time discount | certainty equivalent

A parsimonious and widely held explanation of the advent of farming is that at the end of the Pleistocene, hunter-gatherers took up cultivation of crops to raise (or prevent a decline) in their material living standards (1–3). In this view, the initial cultivation and subsequent domestication of cereals beginning about 12 millennia ago, and the somewhat later domestication of animals (4, 5), is emblematic of the economic model of technical progress and its diffusion (6). Like the bow and arrow, the steam engine or the computer, in this model cultivating plants rather than foraging wild species is said to have raised the productivity of human labor, encouraging adoption of the new technology and allowing farming populations to expand.

Population did increase following domestication (7), but evidence that many of the first farmers were smaller and less healthy than early Holocene foragers casts doubt on improved material living standards as the cause (8). The findings reported here-that the first farmers were probably no more productive than the foragers they replaced, and may have been considerably less productive-favors a social rather than technological explanation of the Holocene revolution, one based on the demographic, political, and other consequences of adopting farming as a livelihood (9-14). The evidence is also consistent with the long-term persistence in many populations of "low-level food production" without a transition to a full reliance on farming (15, 16), as well as with recent evidence that the domestication of cereals was not a one-off event but rather a process extending over as many as 5 millennia [as in the case of rice in China (17)]. The implication is that the process of prehistoric technical advance-whether it be cultivation of crops, the use of fish hooks, or the production of microlithic stone blades-may be explained at least in part by changes in how people interacted with one another rather than simply as a series of innovations in how individuals interacted with nature (18, 19).

The puzzle of the forager-to-farming transition may be considered as either a decision problem—why would a forager initially cultivate plants (perhaps as a small part of the family's livelihood)?—or an evolutionary problem: how would groups that took up farming subsequently reproductively outproduce those who did not? As we will see, the measures of productivity relevant to these two questions are not identical. However, answers to both questions require information about the material benefits and costs of subsisting on cultivated as opposed to hunted or gathered wild species, as these might have been experienced during the late Pleistocene and early Holocene.

There is little question that cultivation increased the output of nutrients and other valued goods per unit of space. The more difficult question, and the one relevant to both the decision problem and the evolutionary problem just mentioned, concerns the productivity of labor rather than of land: was the energetic output (calories) per unit of direct and indirect input of work (henceforth termed "productivity") initially higher for farmers than for foragers?

Data on contemporary and recent foragers exploiting wild species and farmers using hand tools in relatively land-abundant environments, as well as archaeological data, may provide some answers. However, one must first devise an accounting method that will provide a common measure of the returns to human labor expenditure, given the very different technologies involved in cultivation and foraging. Chief among these differences are the degree of delay in returns, the number of species exploited (and hence the extent of risk exposure), and the extent of use of storage, tools, and other intermediate inputs. A second challenge is that even using such a comparable system of accounting, are data from populations in the historical and ethnographic record informative about the relevant costs and benefits of cultivation during the early Holocene?

Statistical Methods

Estimating the Productivity of Labor at the Dawn of Farming. I begin with five distinct facets of this second challenge. First, contemporary farmers—even those with only hand tools—use metal axes, machetes, and other implements that were not available during the early Holocene. The same is true, although to a lesser extent, of foragers. The result may be an upward bias to the farmer-productivity data relative to the forager data. (I have excluded data in which any motorized equipment or firearms were used, but for farmers and foragers alike, it is not possible to exclude data in which any metal implements are used.) Likely biases in the data are summarized in Table 1.

Second, the greater political and military power of farming societies since their inception resulted in the elimination and displacement of late Pleistocene foragers, many of whom had lived in resource-rich coastal, riparian,

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Table 1. Likely bias in using recent data to estimate early Holocene labor productivity

Source of likely bias	Bias	Comment (N, not directly accounted for)
Availability of metal tools	с	N; but modern equipment excluded (e.g., no vehicles or guns for hunters)
Tool and storage facility maintenance excluded	с	N; bias may be small given rudimentary storage facilities and tools
Availability of improved cultivars	с	N; edible fraction of harvest may have been 2/3 of estimated (modern) values.
Marginal habitats of modern foragers	с	N; resources of modern hunters inferior to prehistoric (especially fish and meat)
Farmers' labor intensive resource use	w	Bias limited as effects of land abundance simulated; intensive farming excluded
Farmers' reduced diet breadth (nutrition)	с	Ν
Farmers' reduced diet breadth (increased risk)	с	Hypothetical orders of magnitude for reproductive success estimated
Farmer's reduced spatial mobility (increased risk)	с	Ν
Farming's delayed returns (time discounting)	с	Hypothetical orders of magnitude estimated (both reproductive and subjective)
Farming's delayed returns (others' appropriation)	с	N; bias possibly significant where individual property rights were absent
Foragers' marginal < average productivity(initially)	$W \rightarrow C$	Bias reverses for full scale farming (see text)

A likely bias overstating the relative returns of those exploiting cultivated and wild species is indicated by c and w respectively. Caloric return-rate data for the low-technology cultivation of nongrain early domesticates, such as avocado, bottle gourd, and squash (5) do not exist; these might show higher returns if their limited processing costs were not offset by the greater storage losses.

and other locations with easy access to high-caloric and protein-value fish (especially shellfish) and mammals. Data allowing economy-wide estimates of caloric return rates for these resource-rich foragers do not exist. Thus, available data on modern foragers' return rates may provide underestimates of returns rates for diets rich in terrestrial and maritime wild resources at the dawn of farming.

Third, a bias working in the opposite direction is a result of possible land scarcity among recent farmers: in some of the farming data, the ratio of labor to land is certainly higher than was the case at the initiation of farming. For this reason, the farming return data may underestimate the productivity of the first farmers' labor. However, the fact that the particularly land-abundant economies in the data do not show markedly higher return rates suggests that this concern may be of limited importance; one of the most land-scarce economies, Tepoztlan, Mexico half a century ago, shows the highest returns. In one of the economies studied, the available data permitted an estimate a production function allowing a calculation of the size of the effect on labor productivity of a hypothetical doubling of the land tilled, holding labor input constant (*SI Appendix*). I have used these estimates to account for the effects of presumed greater land abundance in the early Holocene.

Fourth, the food value per harvested crop and the seed yields of early cultivars must have been extraordinarily low; recent levels, which unavoidably are the basis of the estimates here, are the result of millennia of deliberate and unconscious selection by humans. Although full domestic cation of a wild cereal may occur over fewer than 10 (human) generations (20), contemporary cereals and other crops are undoubtedly substantially more productive than the initial cultivars. For example, the grain harvest yield per unit of seed increased at least fourfold in the last seven centuries (*SI Appendix*, Fig. S1 and Table S1). Modern crops are also much improved in the ratio of edible material to the gross harvest. For a stand of wild einkorn (*Triticum boeoticum*, a wheat), the ratio of edible to total harvest was 46% compared with 76% for modern domesticated einkorn (21). The ratio of edible to harvested rice in China rose from 58% four centuries ago to around three-quarters at the mid 20th century (22).

Fifth, although the caloric content of food produced is a convenient common measure across differing populations, it does not fully capture differences in nutrition between foragers and the first farmers, especially the likely greater diet breadth and protein adequacy of Holocene hunter-gatherers compared with the first farmers (23, 24).

Taking these five (and other) unavoidable biases into account (Table 1), it seems unlikely that the available data would understate the productive advantages of farming.

Comparative Accounting Framework. I turn now to the first challenge mentioned above: that of devising an appropriate system of accounting for the inputs and outputs associated with the exploitation of cultivated as opposed to wild species. First, although foragers sometimes built weirs and traps, preserved food, cleared forests, and undertook other investments to enhance long-run returns, delayed returns were more substantial in farming. This, along with the reduced diversity of sources of nutrition in farming populations, meant that farmers made greater use of storage. Estimates of losses during storage using modern data are about 10% of the crop for cereals (and double that or more for cassava and other tubers) (*SI Appendix*).

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Moreover, these technical estimates do not include theft, which may have been significant at the initial stages of farming, except among those lesscommon forager groups already relying heavily on stored resources and adhering to individual possession-based property rights that minimize such losses (for example in California and the Great Basin in the United States and some parts of Australia, and among some fishers).

Farmers' greater use of stored food and storage facilities requires that account be taken of the indirect labor time required to produce and maintain these intermediate inputs. Because most of the farming economies in the sample (by design) make minimal use of tools (not much greater than foragers) and none use animal power (which was not part of the technology of the first farmers), the main differences between farming and foraging in the extent of indirect labor are the result of storage losses and the necessity to set aside seed.

Second, the processing time (dehusking rice, grinding maize) of the early cultivated cereals was substantially greater than for most sources of forager nutrition, sometimes accounting for half or more of the total time use in farming. I include experimentally estimated processing times in the estimates below.

A third difference between the exploitation of wild and cultivated species are the reproductive and subjective costs of the more delayed returns of cultivation. The fact that farming returns are delayed is relevant (albeit in different ways) to both the individual forager's decision (cultivate or not) and the evolutionary success of farming (the relative reproductive success of groups of cultivators). The extent of delay varies depending on the nature of the plants exploited. For cereals with a single crop per year the relevant delay extends from when the labor is performed (clearing, planting, cultivating, and harvesting) to when the crop is consumed, which is distributed throughout the year between harvests. The delay is subjectively costly because people are impatient. It is reproductively costly because of mortality or other reasons for cessation of reproduction) and because of mortality or other reasons for cessation of reproduction) and because ulation growth) (25).

The costs of delay are represented by δ (the annual rate of time discounting), so that an hour of labor input occurring 1 y before consumption of the output has a present value (cost) at the time of consumption of 1 + δ hours. Estimated rates of subjective impatience relevant to the decision problem are substantial, with values of δ in high-income economies in the neighborhood of 0.20 not uncommon (26). Estimates for foraging-horticultural populations in the Amazon and Madagascar are much higher than this (27, 28). Consistent with the view that farming would be unattractive to impatient individuals, among the Mikea in Madagascar, those engaged in foraging exhibited higher rates of impatience in behavioral experiments than did farmers (27). The cost of delay relevant to reproductive value is population growth before the Neolithic demographic transition suggest a fitness-based value of δ of about 2% (7, 29).

Fourth, by reducing diet breadth, cultivation increased risk exposure, for a serious nutritional shortfall is likely to occur if one relies on one or two crops rather than on many wild species. In contrast to farmers, foragers typically exploit a vast number of species of plants and animals (30–32). Those relying primarily on cultivated species face greater risks for two additional reasons: in contrast to foragers, the production cycle for farming extends for long



Fig. 1. Illustration of the certainty-equivalent level of material resources of a particular risk-exposed individual. The estimated w(m) function is the solid curve, where m is the amount of land each woman farms and w is the number of children surviving to age 5. The material resources of this particular woman, indexed by j ($m_i = 17$) would yield $w_i = 7.08$ were the average yields to occur with certainty. Suppose however, that just two states occur with equal probability: yields are equivalent to that which would result from access to 17 \pm 11.69 acres in the two states (good and bad). Then expected fitness is the equal-weighted average of fitness in the good $[w(m^+) = 7.49]$ and bad $[w(m^{-}) = 6.10]$ states, or $w_j^* = 6.80$. Then the certainty equivalent (m_i^*) is the level of resources that, if acquired with certainty, would yield w_j^* : that is, the value of m_j satisfying $w_j^* = w(m_j)$ or $m_j^* = 12.00$, so the risk discount factor for this woman is $\mu_i = m_i^*/m_i = 0.71$. The estimate of μ for the entire population is just the average all of the m_i^* divided by the average m_i or what is the same thing, the average of the $\mu_{j}.$ The algorithm used in the estimates is more complicated than this illustrative example (SI Appendix).

periods, over which risk is more systemic than idiosyncratic. An individual forager may have a bad day or a bad week, but an entire group of farmers more typically would have a bad year or even a bad decade. As a result, foragers may readily smooth their consumption over short periods through reciprocal sharing between the lucky and the unlucky (33). For farmers, by contrast, the systemic and long-term nature of the risk make such consumption-smoothing arrangements both more difficult to sustain and less effective (34). Lacking long-time series and other necessary data on any of the economies for which caloric return data are available, I can do no better than to provide an illustration of plausible magnitudes of the costs of risk exposure.

The uncertainty of the hunt or the harvest is costly because of diminishing returns to nutrition: the (negative) effect on both fitness and subjective well being of a shortfall is greater than the (positive) effect of a surplus of the same size. This fact is sometimes captured by specifying an arbitrary survival minimum and calculating the chances of falling below this level. However, a more flexible method that allows empirical estimation and captures decreasing returns over the entire range of nutrition levels is to let fitness or well-being (w) vary with material resources according to w = w(m), where the function is increasing and concave in its argument: the cost of risk exposure will be greater, the larger the variation in the availability of the population's sources of nutrition and the more concave (more rapidly diminishing returns) is the function w(m).

I estimate the function *w*(*m*) using measures of fitness (children surviving to age 5) and nutritional adequacy (farm land available) among women engaged in low-technology cultivation in Kenya (Fig. 1 and *SI Appendix*, Figs. S3–S5) (35). The extent of temporal variations in resource availability is based on rainfall-based maize yield estimates for precontact farmers in what is now southwestern Colorado over the period 600 to 1300 (36) (*SI Appendix*, Fig. S2). I use the temporal variance of crop yields along with the estimated fitness function to compute the expected fitness of each woman experiencing these variations, and from this number, the level of resources that, if received with certainty, would yield this risk-affected level of fitness (termed the "certainty-equivalent" level of resources).

The risk discount factor is then $\mu = m^*/\underline{m}$ where m^* is the population average of the individual women's certainty equivalents and \underline{m} is the average resource availability. Multiplying observed average caloric yields by μ gives the yields that, if received with certainty, would be equivalent in fitness or well-being terms to the observed data subject to weather-induced temporal variations. Equivalently, $1/\mu$ (> 1) gives the mean availability of a resource exposed to risk that would yield the same fitness as one unit of the resource received with certainty.

Fig. 1 illustrates how the estimate of risk exposure and the fitness function allow the estimation of a cost of risk exposure for a single individual exploiting a single species. The risk discount used in the estimates presented below is based on farmers exploiting not one (as in this example) but two crops with uncorrelated shocks and experiencing the full range of predicted (nonnegative) yields rather than just a good and a bad state (*SI Appendix*).

The farmers' risk exposure is estimated on the assumption that they exploit two species of equal importance in their diet, each with a yield variability as estimated above, assumed to be uncorrelated across the crops (thus downward biasing the estimate of risk exposure, given that shortfalls in one crop are very likely to be associated with generalized shortfalls). We perform the same procedure for the exploitation of wild species, but assuming that each of nine animal and plant species are subject to the same variations in availability, as are the rainfall-estimated maize returns. Using "f" and "h" superscripts to refer to farmers and hunter-gatherers, respectively, the above calculations (*SI Appendix*) give: μ^{f} = 0.92 while μ^{h} = 0.98, meaning that the certainty-equivalent reduction in productivity is 8% of the average labor productivity for farmers and 2% for foragers. [In the *SI Appendix*, I show that an alternative calculation using annual data on actual wheat yields between 1211 and 1349 in England gives values of μ^{f} = 0.86 and μ^{h} = 0.96, indicating a greater risk

Table 2. Computing risk-adjusted and time discounted labor productivity for cultivated plants

Variable	Signifies
с*	= {certainty equivalent of nutrition}/{processing and present value of direct and indirect labor input} = $Kfc\mu/H(p + s(1 + \delta d))$, where
К	Gross kilogram of output
Н	Hours of cultivation labor
f	Fraction of unprocessed cereal that is edible and is not lost in processing
с	K calories per kilogram of processed cereal
μ	Ratio of certainty-equivalent to the mean calories attained
р	Ratio of total processing time to direct cultivation time (P/H)
δ	Annual discount rate for production (not processing) time
d	Average delay between cultivation and consumption (fraction of year)
s	Ratio of gross harvest to net cereal available for processing (net of storage losses and seeds)

Virtually all available data report or allow the calculation of the mean gross kilograms of unprocessed output (*K*) per hour of direct cultivation labor (*H*). For the needed measure—the present value of certainty-equivalent calories per total hour of work—the following must be done: (*i*) account for the food content of the harvest, namely the part that is edible and not lost in processing (*f*); (*ii*) convert kilograms of edible processed cereal to kilocalories; (*iii*) express the resulting nutritional value in certainty equivalent terms (μ); (*iv*) add both processing time (*pH*); and (*v*) the indirect labor namely that required to produce a kilo of stored cereal ready for processing, given the extent of storage losses and seed requirements [(*s*-1)/*H*]; and (*vi*) express this (nonprocessing) labor as a present value at the time of consumption to take account of the fact that it (but not processing labor) occurs before consumption (1+ δd). (The assumption that no processing is done before storage may upward bias the estimate of *c** as it implies that no processing time occurs in advance of consumption or is expended on cereal lost in storage). The estimates in Fig. 2 do not make adjustment for time delay and risk and so $\delta = 0$ and $\mu = 1$.

exposure disadvantage of farming than the estimates I used. An alternative estimate of the fitness function w(m) (*SI Appendix*) finds a substantially greater degree of concavity than the estimate used here, and would therefore imply greater differences between foragers and farmers in the costs of risk exposure.]

The fact that cereals and other early cultivars may be stored over more than a year mitigates risk exposure: the farmer who stores sufficient cereal so that each year's consumption is based on a harvest of 2 y rather than just 1 y has diversified risk in a way similar to exploiting a larger number of species (assuming that shocks are uncorrelated across species and from year to year). However, storage exposes the farmer to approximately equivalent losses (thefts, pests, rot) and so does not substantially reduce the risk problem (*SI Appendix*).

Results

Taking account of the above requirements for statistical comparability, I use the algorithm in Table 2 to estimate the labor productivity data in Fig. 2 and Table 3.

The estimates taking account of risk and delay appear in Table 3. In addition to the data with no adjustment for risk and delay (line 1, summarizing the data in Fig. 2), I distinguish between the decision problem and the evolutionary problem (results shown in lines 2 and 3, respectively). For the former, capturing the lone forager family's decision to commit modest resources to cultivation, I adjust the cultivated species' returns downward by the substantial subjective cost of delay. However, because a minor commitment to farming would not significantly reduce the number of species exploited, I apply the very modest foragers' risk adjustment. For the evolutionary problem—how would a group of farmers out produce a group of foragers?—I apply the farmers' fitness-based risk adjustment and the much lower fitness cost of delay based on mortality and reproductive value. Average productivity levels in cultivation appear to be in the neighborhood of three-fifths of the returns to foraging wild species, depending on the adjustment.

Discussion

What can we conclude from this evidence? No single estimate can possibly capture the likely benefits and costs of cultivation for the particular species and the locally specific abundance of wild resources, climate, and other conditions under which the archaeologically documented cases of farming first occurred. Moreover, available estimates are necessarily subject to considerable error. However, the evidence presented here is not consistent with the hypothesis that at the dawn of farming the productivity of labor in cultivation generally exceeded that in foraging; indeed it suggests the opposite. This conclusion is especially the case when account is taken of risk exposure and the more delayed nature of agricultural production; however, it holds even in the absence of these adjustments.

If farming was not more productive than foraging, then we need to consider alternatives to the paradigmatic economic "farming was a better way to make a living" explanation of the Holocene technological revolution. The hypothesis of piecemeal adoption of cultivation (15, 37–39), along with the demographic



Fig. 2. Net kilocalories per hour of direct and indirect labor, c*: wild and cultivated species. Methods and sources appear in *SI Appendix*, Table S2. Excluded are return rates for wild species in cases where atypically rich resource concentrations were encountered or where data were available for one sex only or for a limited span of time. Solid bars give returns for the exploitation of a large number of wild species. All cultivated yields are multiplied by 1.079 to adjust for the likely effect of greater land abundance in the Late Pleistocene.

Estimate	Cultivated (1)	Wild (2)	$P < (for \Delta wild - cultivated)$	Ratio (1)/(2)
No risk or time delay adjustment (Fig. 2)	1,041 (152)	1,662 (590)	0.005	0.63
Decision: forager risk only and subjective delay	954 (147)	1,628 (578)	0.0003	0.59
Evolution: risk and reproductive delay	951 (139)	1,628 (578)	0.0003	0.58

The estimates relevant to an individual's initial decision to engage in some farming (line 2) entail no greater risk for the farmer ($\mu = 0.98$) than for the forager. The estimates relevant to average reproductive output for a group of farmers (line 3) account for the greater risk exposure of farmers ($\mu = 0.92$). The subjective and reproductive delay costs are $\delta = \{0.20, 0.02\}$ respectively. The *P* value for the difference between the wild and cultivated *c** distributions are from the Wilcoxon rank-sum test (not affected by the possibly exaggerated returns in the Great Basin prehistoric data). The Welch-Satterthwaite difference in means *t* test (unequal sample variances) gives (for the three rows in order): *t* = 2.33, 2.38, and 2.39 which even given the very limited degrees of freedom (4.2) are significant at *P* < 0.078, 0.055, and 0.054. SDs in parentheses.

or political (rather than labor productivity) effects of farming may provide part of an explanation.

The answer to the decision question-why did the first farmers farm?-provided by the piecemeal adoption hypothesis is convincing. For an erstwhile full-time forager to benefit by farming a little and foraging a little less, it is not required that the labor devoted to cultivation be more productive than the average of the foraging activities. Foraging a little less would mean forgoing the lowest-ranking components of the diet (that is, the wild plants or animals with the lowest caloric return rate as measured here). Thus, the decision-if and how much to farm?-depends on a comparison of the marginal (not the average) productivity of the two pursuits. The optimal distribution of working time between foraging and farming, that which would maximize total energetic yield (adjusted for risk and delay) for a given amount of labor input, equates these marginal productivities. Although no estimates of the relevant marginal quantities are possible, in a population that is engaged almost entirely in foraging, the marginal productivity of foraging labor is likely to be substantially lower than the average productivity (40). Thus, the data presented here (Fig. 2 and Table 3) do not preclude farming as a minor component of the livelihood of a population engaged primarily in foraging, as is widely observed in both the archaeological and ethnographic record (15, 27, 37, 39).

However, this distinction between marginal and average productivity does not reconcile the estimates reported here with the fact that in many populations farming would subsequently become the main source of livelihood (the phenomenon we are trying to explain). The problem is that the marginal calculation that initially favored a little farming would reverse once farming became the major source of livelihood: at that point, the few foraged resources that were still exploited would be the highest ranked of the full spectrum of once-foraged resources. The farmer-forager family considering devoting even more labor to cultivation and less to foraging would compare these high marginal foraging returns with the prospective returns to cultivation on patches that were not yet considered productive enough to be used. Thus, once farming came to occupy a substantial fraction of the farmer-forager's labor, the

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marginal productivity of farming labor would be below the average productivity reported here (because of increased travel time, even if good quality land was abundant), and the marginal productivity of foraging higher. The result is that as farming became more extensive, the bias of looking at average rather than marginal productivity is reversed and the reduction of foraging to insignificance becomes difficult to explain.

However, an evolutionary argument may be able explain the eventual spread of farming once it was adopted in a few places. Because of extraordinary spatial and temporal variations in weather, soil quality, scarcity of wild species, and other conditions that could make farming rather than foraging an efficient provisioning strategy, it is likely that a few groups would have found it advantageous (by the marginal conditions above) to take up farming as their primary livelihood. Then, in order for farming subsequently to be adopted by other groups-the evolutionary problem-farming need not have lessened the toil of subsistence. Even if health status and stature declined, the lesser mobility of farmers would have lowered the costs of child rearing (41). This lowering could have contributed to the dramatic increase in population associated with cultivation (7) and, hence, to the spread of farming (12). Or the fact that agricultural wealth (stored goods and livestock particularly) was more subject to looting may have induced farming groups to invest more heavily in arms and to exploit their greater population densities, allowing them to encroach on and eventually replace neighboring groups (11).

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Supporting Information for

The cultivation of cereals by the first farmers was not more productive than foraging

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1. Simulating the effect of greater land abundance

Many of the data sets used to estimate caloric returns to labor are for shifting agriculture with little land scarcity, perhaps replicating early Holocene conditions and hence not greatly biasing downward the estimates of labor productivity. But one suspects that early Holocene farmers may have enjoyed even greater land abundance, thereby downward biasing an estimate of labor productivity based on these data compared to what it would have been among the first farmers. To account for this possible bias I estimate the likely effects of land scarcity on the productivity of labor and use this estimate to adjust upwards the cultivation returns estimates.

If the marginal productivity of land is positive, increased use of land (holding labor input constant) will increase labor productivity (output per hour of labor). To assess the effects on labor productivity of the greater land abundance that may have characterized early the Holocene conditions under which the first cultivation took place, consider the production function

$$Q = qT^{\alpha}H^{\beta}$$

where Q = total output (kg), T = area of land tilled (ha), H = direct labor devoted to cultivation(hours) and q, α , and β are positive constants to be estimated. Using this equation, we see that increasing T (with H constant) by n-fold will increase the average product of labor by n^{α} -fold.

An unusual data set providing individual family data on hours worked by age group, land tilled and output allowed the estimation of this equation for the extensive cultivation of late millet by a horticultural population in 1949 in a remote area of The Gambia.(1) The estimated equation, with H a measure of total weighted hours with weights of 1/3 for workers less than 11 years of age and older than 60 and 2/3 for those 11-15 and 50-60 (with standard errors of estimates in parentheses) follows.

lnQ = 1.21 + 0.80lnH + 0.11lnT R² = 0.49, n = 19(1.72) (0.30) (0.30)

The effect of variation of the labor input on output is large and statistically significant ($\beta = 0.8$ indicates that a ten percent increase in labor input is associated with an eight percent increase in output). But the estimated output response to variations in land ($\alpha = 0.11$) is small and not

significantly different from zero. The equivalent equation with unweighted total hours is virtually identical; including the number of plots farmed by the family as a co-variate (to control for travel times) reduces the coefficient of land to 0.05 (weighted) and 0.03 (unweighted), both not significantly different from zero. Using the estimate of $\alpha = 0.11$ implies that doubling the land input would increase labor productivity by less than 8 percent (2^{0.11} = 1.079). A similar estimate from a group of pastoral-horticulturalists in Ethiopia (2) gives $\alpha = 0.04$ (also not significantly different from zero), implying that doubling the land input would raise labor productivity by less than 8 percent (2^{0.04} = 1.028). I use the larger estimate (1.079) to adjust upwards all of the cultivators' return rates.

One would like to be able to make a similar adjustment for modern forager productivity to account for the undoubtedly less productive environments in which they now live as well as restrictions on their geographical mobility as a provisioning strategy due to circumscription by farmers and national boundaries, but data do not allow this.

2. Cultivation, Processing and Indirect Labor Inputs

Three categories of labor are accounted for. The direct cultivation labor generally provided in the data (*H*), processing labor (*P*) and indirect labor (*I*), the later comprised of the labor involved in producing goods that will not be processed as food (lost in storage or set aside as seed). For reasons explained below I ignore the indirect labor involved in producing and maintaining tools, fencing (where relevant) and storage facilities. Processing labor occurs (I assume) at the time of consumption, while cultivation and indirect labor occur in advance of consumption. As I calculate (in Tables 2 and 3) the return to labor estimate as a present value at the time of consumption (rather that discounting this to the time of cultivation), the labor expended at an earlier date must be augmented by $(1 + d\delta)$ where δ is the annual rate of time discount (rate of time preference) and *d* is the average period of delay between cultivating and indirect labor on the one hand and consumption on the other, expressed as a fraction of a year. Thus the present value (at the time of consumption) of the indirect and cultivation labor (occurring earlier) is $(I + H)(1 + d\delta)$ and the total labor input is $P + (I + H)(1 + d\delta)$. This is equivalent to discounting the returns (that is, the caloric value) to the time at which cultivation and indirect labor time is committed. It understates labor time if some of the processing time occurs prior to consumption (as occurs in the case of husking maize and removing kernels from cobs).

Indirect labor. Tool use is minimal for both the farming and foraging societies under consideration. For example, the sticks that Hadza women (in Tanzania) use digging for tubers take on average 4.2 minutes to make (3) and they are discarded on the average after 24 hours of use giving a ratio of indirect to direct (foraging)labor time of 0.003. While digging stick production with stone tools would take substantially longer, the contribution on total labor time would nonetheless remain small enough to ignore. Among the Hanunoo farmers (Philippines (4):147) "a minimum inventory of essential moveable farming implements ...would include three sharpened sticks (a dibble, a planting stick and a digging stick, each of which is a temporary artifact ordinarily made on the spot by the user and discarded after a brief period of time), an axe for clearing, a work knife and several basket containers." Beyond the production and maintenance of these implements the only substantial tool investments among the Hanunoo are rice storage facilities. Comprehensive estimates of tool maintenance times are not available. This component of indirect labor is perhaps somewhat greater among farmers than foragers (due to the importance of storage facilities and fencing or field guarding where relevant), but the magnitudes are certainly small enough to ignore.

This is not the case for the indirect labor involved in the production of gross output that will be lost in storage or set aside for seeds. Let s > 1 the quantity of the gross harvest required for one unit of unprocessed grain to be available for processing at the time of consumption (taking account of storage losses and seed set-aside). Then we need to account for the indirect labor, namely (s-1)H, that produced the required seed and the storage losses. What are termed "minimal" estimates of late 20th century post-harvest losses including in storage from a global survey (5):167 were one-tenth for cereals and other durables and one-fifth for tubers and other perishables, not including theft and seed use. (Other estimates for root crops suggest much greater storage loss.) Adequate data on losses to theft do not exist.

Data on seed use as a fraction of output are provided in a few studies, and these range from 1 to 8 percent for 20th century farmers, with much higher values estimated for cereal production in

early modern Europe. See Table S1 and Figure S1. On this basis I estimate that post-harvest deductions are: storage losses v = 0.10 and seeds requirements $\omega = 0.05$. A plausible alternative estimate based on the wheat, barley and oats seed productivity calculated from annual data from the Rimpton manor in England between 1211 and 1268 gives a much larger seed requirement: $\omega = 0.23$ (st dv 0.10). Using $\omega = 0.23$ (instead of $\omega = 0.05$) would reduce the mean c^* estimate for the cultivated species in Figure 2 and Table 3 by five percent.

To calculate the gross harvest (X) required to make an amount Y available for processing following storage note that the latter is equal to $X(1-\nu)(1-\omega)$ because $X(1-\nu)$ is the harvest remaining after storage, and of this only the fraction $(1-\omega)$ is available for consumption because ω of this must be set aside for seed rather than consumed. Thus $s = X/Y = 1/\{(1-\nu)(1-\omega)\} = 1.17$, and I + H = sH = 1.17H. Total labor input expressed as a present value at the time of consumption is therefore: $\{P + s(1 + d\delta)\}H$.

Processing labor. Cooking and eating are not included in processing labor. There are two kinds of processing cost: some part of the unprocessed cereal is inedible or lost in processing, and processing requires work. Recall from the main text that 46 percent (by weight) of the harvest of a stand of (wild but subsequently domesticated) einkorn (*Triticum boeoticum*) was edible.(6) An estimate the fraction of the harvest that is edible and not lost in processing (*f*) for rice based on Chinese data half a century ago was f = 0.75, and for all cereals during the 1930s in Indo China, Japan, Philippines, India and Java f = 0.79, while Chinese historical records from the 15th century give f = 0.58 for rice.(7) Because einkorn was a minor crop in the forager to farmer transition, and so as to avoid underestimating the returns to cultivation, I use the historical estimate for rice (f = 0.58) and f = 0.79 for all other crops except sorghum in Cameroun for which the source provides an estimate (f = 0.84).

Evidence on processing time differs across species and is typically given in hours of labor per kilogram of unprocessed output. Processing time for hunted animals is an insignificant fraction of total time while for gathered species one estimate based on extensive data finds that processing constitutes 11 per cent of total (women's) gathering time.(8) Foragers making extensive use of seeds and nuts devote much more labor to processing (on a par with maize cultivation, or even more, for example, in the case of acorns) but none are represented in the data set. The substantial magnitude of processing cost for farmers is suggested by maize cultivation in Mexico in 1944.(9) Cultivation yielded 1.58 kilograms per hour of cultivation labor, of which 1.35 kg would be processed (the rest set aside as seeds or lost in storage prior to processing) requiring (according to experiments with stone tools(10):72) 1.73 hours grinding per kg of harvested maize, or a total of 2.35 hours (= (1.35)(1.73)) to process the product of an hour's cultivation labor. Husking and shelling times are not included in this estimate of grinding time.

An estimate of the hand-tool processing costs of rice is available from agronomists' studies of the Tonkin delta in the 1930s. Gourou reported (p.241) that an hour of human labor yields a third of a kg of processed white rice, and data presented by Dumont imply that an hour of cultivation labor yielded k=0.79 kg of harvest (somewhat less than the average of 0.88 in the rice estimates used here), a third of which (by weight) would be lost in processing (p.138)(11, 12) Together these data imply that the 0.33 kg of processed rice cited by Gourou was (before processing) 0.5 kg of harvest which would have required 0.385 hours to produce and 0.615 to process. So it would take 1.23 hours to process a kg of harvested rice. If the loss rate in harvesting is not one third, but the quarter estimated for China in the mid 20th century(13, 14) processing time is 1.47 per kg. I use the lower rate. Estimates for c* from the Tonkin delta are not used both because land was (even then) relatively scarce and draft animals were used (though not extensively).

For the millet and sorghum I use the de-husking (but not the very substantial groat grinding) time estimated experimentally, namely 1.09 per kilo of unprocessed cereal (this is the midpoint of the estimates in Wright's Figure 4.(14)

Additional information on methods and sources used to calculate the caloric return rates in the text appear in Table S2.

3. An alternative data set on foragers and farmers time and energetic inputs

An alternative datum, total working time and total energetic input to working activities may provide information about the productivity of differing production systems if the resulting level of subsistence is similar among the systems compared. A shortcoming of these data is that the mapping from production systems to the nature of species exploited (foraging wild species, vs cultivating) is not exclusive: low-technology farmers for example, devote significant time to hunting and gathering wild species and groups classified as foragers often do some cultivation. Comparisons by specific activity (forager activities such as skinning a seal, hunting pigs, collecting leaves and analogous horticultural and agricultural activities like clearing land, casting seed, planting) found that foragers' and horticulturalists' production energy expenditure relative to rest (PAR) per hour of work was equivalent while agriculture was significantly higher.(15) Total daily energy input among horticulturalists was 8 percent greater than among foragers. Agriculturalists (distinguished in table S3 from horticulturalists by the use of draft animals and commercialization of production) are included here for reference; they devoted 60% more energy to production daily (Table S3.) But it is the horticultural-forager comparison that is arguably relevant to the forager-to-farmer transition studied here.

4. Cultivating and foraging einkorn.

The forager-to-farmer transition involved a significant shift in the species exploited. But the concomitant alteration in technology is nicely illustrated if we consider just a single species– einkorn – that was almost certainly exploited opportunistically by foragers in Anatolia before it was cultivated and eventually domesticated. (It was not a major cultivated crop but was similar in both its wild and domesticated variants to emmer, which was.) Harlan harvested this wheat by hand, and also more efficiently using a reconstructed flint sickle of the kind that would have been available to early Holocene farmers.(6) I use his and other evidence as the basis for the following speculation.

Suppose that the cultivation of einkorn as a staple involved the maintenance of a sickle, sedentary residence, delayed consumption, reservation of some output for seeds, storage, and a degree of risk exposure associated with substantial reliance on a single crop. By contrast suppose that foragers consumed the grain (as one of many species making up their diet) when a suitably rich stand ripened; and that forager harvesting of einkorn involved neither specialized tools nor storage but incurred both travel time to dispersed stands of einkorn and less effective harvesting due to the lack of a tool specialized for the job.

Harlan harvested 2.05kg/hr by hand and 2.45 kg/hr using a flint sickle.(6) In the

calculations that follow, parameters common to farming and foraging are: c = 3567, f = 0.46 (Table S2) and for farmers (as above) seed requirements and storage losses result in s = 1.17. I assume that replacing or maintaining broken flint sickle blades required 3 minutes for every hour of harvesting. Travel time for the foragers was estimated as 14.4 minutes per hour of harvesting (based on Hadza foragers travel times in gathering //ekwa.(16): 344) The first farmers surely did not have as fine a flint sickle as Harlan used, but they probably quickly became more adept at harvesting; I assume these two omitted effects may be offsetting. I assume that foragers and farmers of einkorn had access to the quality distribution of stands of the type Harlan harvested, but that foragers would have bypassed the one "thin stand" (of 5) in favor of higher valued items in the diet.

These calculations (Table S4) following the algorithm in Table 2 shows that, for plausible parameter values, the delay- and risk-adjusted returns to the einkorn farmers would not have exceeded those of the forager and more likely would have been somewhat inferior.

5. Risk exposure

Both a forager's motivation to take up farming and farmers' ability to reproductively outcompete groups exploiting wild species may have been limited by the greater degree of risk exposure arising from the limited number of species that farmers exploited. Thus we need to take account of differences in well being (relevant to the farmer's decision problem) or fitness (relevant to the evolutionary success of farming) due to risk exposure experienced over long periods (yearto-year or decade to decade, for example, not day-to-day or week to week). The forager-farmer difference in risk exposure that I will estimate is based entirely on the difference in the number of species on which the individual relies, thus setting aside the generally superior risk reduction methods available to foragers due to their mobility and the less delayed nature of their provisioning strategies mentioned in the text.

Adjusting for risk exposure requires four estimates to take account of: a) the effect of exploiting a smaller number of species; b) the likely degree of variation in the abundance of a single species; c) a conversion factor to translate the estimated variation the abundance of a single species into equivalent variations in the measure of resource availability affecting individual fitness

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or well being, and d) the effect of the resulting variation in total resource abundance on the fitness or well being of an individual

a) *The effect of exploiting a larger number of species*. Suppose the farmer exploits two species (or equivalently a larger number experiencing identical shocks) and the forager nine. The two-species number for farmers is of course subject to significant variation; one estimate from the Hopi indicates that 71 per cent of calories were derived from a single crop, maize, but this may not be typical.(17) The nine-species estimate for foragers is based on diet studies of the Paraguayan Ache foragers during 1980-1982 (just a decade after contact) indicating exploitation of 84 species and a substantial reliance on at least 9 species(18). The Ache data may understate the degree of species diversity in the Late Pleistocene forager diet. A half century ago, aboriginal people on Groote Eylandt (in the Bay of Carpentaria in Arnhem Land, Northern Australia) consumed 25 species of land animals (including reptiles), 75 birds, 97 fresh water and marine animals and fishes, 37 shellfish, and 75 plants (a total of 309)(19):15.

Each of the species assumed to make up the diet (wild and cultivated alike) is assumed to be subject to differences over time in their availability due to such things as climatic variation and disease, leading to variations in both crop yields and encounter rates of hunted and gathered species. If the farmers' and foragers' sustenance (respectively) is the equally weighted sum of 2 or 9 independent draws from the same distribution of species with unit standard deviation, then the standard deviation of the distribution experienced by each individual forager is one third $(1/9^{\frac{1}{2}})$ and by farmers is $0.71 (1/2^{\frac{1}{2}})$ so the farmer's risk exposure is a bit more than twice that of the forager.

b) *Temporal variation in the abundance of a single species*. I estimate the variation over time of species availability from the predicted annual maize yields (Figure S2 and Table S5) among pre-contact native Americans, using (tree-ring based) rainfall data for the years 600-1300.(20), smoothed using a 21 year moving average so as not to overstate variation and to minimize the effect of measurement error. The resulting data are (in kg/ha): mean yield 254.0, minimum 204.7 and standard deviation 17.6. To measure the level of risk exposure I normalize these temporal variations in predicted yields by the size of the surplus, that is, the standard deviation of yields divided by the excess of the mean over the minimal yield observed over the

period, namely the minimum of the 21 year moving average data (204.7 kg/ha). This minimal yield would produce less than 500 kcalories per hour of production and processing labor, using an estimate of 768 hrs per hectare (the least labor-intensive of Barlow's estimates for hoe cultivation of maize,(10):71) and the other parameters in table S2) The resulting number – the risk exposure ratio: 0.35 = 17.6/(254-204.7) -- is nonetheless likely to be an underestimate for two reasons. First, the rainfall-predicted yields do not capture other sources of crop-yield variation such as disease and pest infestations, and as a result show a smaller degree of variation than do actual yields for years in which measures of both actual and predicted are available (1931-1960). Second, the data are averages for a 1816 km² area and thus smooth out many of the variations at the individual farm (or village) level.

Not surprisingly, in light of these considerations, data from a single (large) farm, the Rimpton manor in medieval England between 1211 and 1349 (Table S6), based on the actual wheat yields (recorded by the *granatarius*) yielded an alternative (superscript A) risk exposure of 0.49 (or 40 per cent greater than the estimate above.(21))

c) *Conversion factors*. To estimate the standard deviation of the distribution of the resource availability faced by each woman (σ^{k}) we need to convert the standard deviation from the time series of maize yields (σ^{c} , in kg/ha) to a measure of the standard deviation of resource availability to the women for whom we have data on reproductive success (acres). (The basic data are in Table S5.) I assume that the risk exposure ratio of a single resource (species) exploited by the women is the same as that estimated for the Colorado maize farmers or

$$\sigma^{k}/(m - m^{-})^{k} = \sigma^{c}/(m - m^{-})^{c}$$

where the superscripts {k, c} refer to the Kenya and Colorado data sets respectively, and {m m^{-} } are respectively the mean and minimum of the resource availability in the two data sets. For the Kenya data set the minimum is the resource availability for which estimated fitness is zero (0.02 acres), a figure no doubt reflecting considerable within-extended family sharing. Thus we have (for a single species)

 $\sigma^{k} = 17.6(17.1-0.02)/(254.0-204.6) = 6.08$ acres

Taking account of the greater number of species exploited by the hunter than the farmer (9 and 2 respectively) the standard deviation of material resource availability for the two livelihoods is thus

 $\sigma^{h} = 6.08/9^{\frac{1}{2}} = 2.026$ $\sigma^{f} = 6.08/2^{\frac{1}{2}} = 4.297$

The alternative Rimpton manor data set (indicated by the A superscript) gives the following estimates (which were not used in the calculations below).

 $\sigma^{kA} = 0.0886(17.1-0.02)/(1.0378-0.8646) = 8.7187$ $\sigma^{hA} = 8.7187/9^{\frac{1}{2}} = 2.9062$ $\sigma^{fA} = 8.7187/2^{\frac{1}{2}} = 6.1651$

d) The effect of variation in resource availability on fitness or well being. To complete the calculation we need an estimate of the effect of the level of resources available to an individual m_i on her reproductive success or subjective well being w_i . Estimates of the w(m) function are based on the reproductive success of women rather than both sexes because we are interested in the effect of resource availability on the reproductive output of a group, not of individuals *per se*. Abundant resources contribute to male reproductive success in acquiring mates (which may be subject to increasing marginal returns), increasing his share of the total reproductive output of the group without having any determinant effect on its magnitude.

The function w = w(m) is assumed to reflect also the individuals' subjective well being, a not implausible assumption for populations prior to the demographic transition. Its estimated concave functional form (see Figure S3, below) with pronounced and rapidly decreasing returns to increased material abundance at very low levels of abundance (but not for greater abundance) is also typical of measures of subjective well being as a function of income.

The data are from 206 women farmers of the Kipsigis people in Kenya.(22) Let m_i and w_i respectively be the woman's reproductive success (number of children surviving to age 5) and available resources (measured in acres of land). Because we are interested in "how concave" the relationship is, I estimated

$$w_{i}=\alpha+\frac{1}{1-\rho}(m_{i}^{1-\rho}-1)+\varepsilon$$

using non-linear least squares, finding a value of ρ equal to 1.08 (p < 0.001), which indicates that the fitness function exhibits somewhat more sharply diminishing returns than the logarithmic

function: $\partial w / \partial m = 1/m^{\rho}$ rather than $\partial w / \partial m = 1/m$ in the logarithmic case (Figures S3-4). The estimated value of α is 4.54 (p<0.001). Data on the size of garden plots of Chewa women horticulturalists in Malawi and the number of children born to each (23) yield an alternative estimate of $\rho = 1.88$ (p<0.001), indicating a much more concave function and hence much greater cost of risk exposure, implying a relatively larger downward adjustment of the farmers caloric returns (compared to the foragers). The (less concave) Kipsigis based estimate is used in the computations underlyinng Figure 2 and Table 3.

To calculate the effects of risk exposure on reproductive success I assume that the women each experience a distribution of resource availability that for each species is normal with a mean equal to the woman's actual acres, and a standard deviation of $\sigma^{h} = 2.026$ and $\sigma^{f} = 4.297$ respectively for those hypothetically exploiting 9 wild and 2 cultivated species respectively. The expected fitness of each variance-exposed individual is then calculated by transforming a normal distribution (with a mean of the individual's expected resources and the standard deviation calculated as above, making use of the fact that foragers exploit nine and farmers two species) into a discrete 33-bin distribution of resource levels and then weighting the fitness associated with the *m* for each bin by its frequency in the discrete distribution (and assigning zero fitness to those cases in which m < 0.02 acres, the level predicating zero fitness.) The expected fitness of each individual is then converted to a certainty equivalent as described in the text, and these are then summed and divided by the number of women to give the average certainty equivalent of the population a whole. A detailed description of the computations follows.

I first discretize the normal distribution. Consider the case of a woman with the population mean acres (17) and assume that the distribution of shocks is supported over \pm 16. Then categorize the acres:

 $\{1\},\{2\},\{3\},\dots\{33\}.$

Let F be the cumulative distribution function for a normal distribution with mean = 17 and standard deviation of σ^{f} and σ^{h} for the farmers and hunters respectively. We then assign probabilities to each resource availability category.

 $Pr(\{1\}) = F(1.5),$ $Pr(\{2\}) = F(2.5) - F(1.5),...$ $Pr((\{33\}) = 1 - F(32.5)$ The top panel of Figure S5 shows the discretized distribution of resource availability for a woman with the mean level of resources. For women with greater (lesser) resource availability we shift the distribution to the right (left).

When the acres of a given woman is less than 17, we adjust this discrete distribution by assigning the probability with which all negative values occur to a resource availability of 0.02 (minimum acres which ensures 0 fitness) occurs. For example, when acres farmed is 8, by shifting the normal distribution to the left by 9 acres we obtain the distribution in the middle panel of figure S5. We then reassign the negative values to m = 0.02 (bottom panel) arriving at the distribution used for this woman in our calculations. Thus we obtain the following distribution.

Discrete point (m _i)	0	1	2	3	4	etc
Probability (p _i)	0.10	0.035	0.04	0.05	0.05	etc

Using this method to find the discrete distribution for each woman, we then calculate each woman's expected fitness, and based on that, the certainty equivalent level of resources for each woman, using the equations in the table below. Finally the risk discount μ is the population mean of the certainty equivalents divided by the mean resource availability.

Expected fitness of each woman as a function of the fitness of each level of resource availability weighted by its probability, p_j^{i}	$w^{\textbf{*}}_{\textbf{i}} = \sum_{\textbf{j}} w(m^{\textbf{i}}_{\textbf{j}}) p^{\textbf{i}}_{\textbf{j}}$
Certainty equivalent level of resources for each woman	$w(m_i^{\bullet}) = w_i^{\bullet}$
Risk discount: the ratio of the mean certainty equivalent for the entire population divided by the mean resource availability	$\mu = \frac{m^*}{\underline{m}}$

The results are in Table S7, along with results based on the alternative series of crop yields from the Rimpton manor.

6. *Would multi-year storage among farmers increase expected fitness?* The answer depends on whether the gains from consumption smoothing made possible by diversification

(across years rather than species) exceeds the multi-year storage losses. To see how two-year storage might work, we can compare two farmers. Impatient stores just from harvest to harvest, so (in expectations) the store is empty at the time of the next harvest. Thus he and his family consume the harvest at t= 0 (that is, h_0) minus storage losses at rate v over the inter-harvest period or $(1-v)h_0$. Prudent stores over a two-year period so that at the time of the harvest (t= 0) his store contains the half of the harvest of the two previous years (minus storage losses) and his family consumes half of h_0 plus half of $h_{.2}$ (both minus storage losses) or $\frac{1}{2}\{(1-v)^3h_{.2} + (1-v)h_0\}$ The remaining store (namely $\frac{1}{2}h_{.1}$) remains in the store to be consumed in t =1 along with half of h_1 (both adjusted for storage losses). So the expected fitness of the two, setting the expected harvest in each year = 1 and , letting $\mu(x) \in (1,2)$ be the risk discount factor for Impatient (1) and Prudent (2), are in t = 0 (and all future years) proportional to :

Impatient: $z^{I} = \mu(1)(1-\nu)$

Patient: $z^{P} = \mu(2)^{1/2} \{ (1-\nu)^{3} + (1-\nu) \}$

Using the risk discounts in table S7, we find that $z^{I} = 0.77 > z^{P} = 0.75$ so multi year storage does not increase fitness. However using the estimated variance from the Rimpton manor (risk discounts in parentheses in table S7) we have $z^{I} = 0.70 = z^{P}$. So multi year storage has no effect on fitness. Were we, however, to estimate the risk discount factor using the much more concave alternative fitness function ($\rho = 1.88$ estimated from Malawian data rather than the $\rho = 1.08$ based on Kenyan data), risk mitigation would contribute much more to fitness, and as a result two-year storage would increase expected fitness. But the conditions under which multi-year storage would be fitness enhancing are precisely those (highly variable returns and strongly adverse fitness effects of shortfalls) that would reduce the risk-adjusted productivity of farming compared to foraging.

Table S1. Estimates of seed use as a fraction of gross output (ω), 1211-1978.

Source	ω	Comment
England 1211-1268 (21)	0.18 0.22 0.29	Wheat (st dv: 0.07) Barley (0.10) Oats (0.11) (all calculated from Appendix)
Europe 1350 (24)	0.32	Wheat 1350 p 78.
UK 1450 (25)	0.18	Wheat: Bennett's modification (p. 65-66) of Gregory King's estimate (20%).)
Europe 1850 (24)	0.11	Wheat 1850, p 78.
Mexico 1944 (9)	0.011	Maize: seed requirements as a percent of gross output on medium land, p.144).
Malaysian Borneo 1952 (26)	0.05	Paddy required as seed for next season, p.103
Philippines 1952-4 (4)	0.035	Rice: midpoint of range of seeds/harvest p. 119
Haute Volta 1959 (27)	0.036	Cereals (Sorghum primarily):p. 64)
Cameroun 1955-7 (28)	0.02	Sorghum: p. 253.
China 1977-78 (13)	0.022 0.073 0.033 0.084	Rice Wheat Corn other cereals, all from p.68

Table S2. Caloric output available for consumption per unit of total direct and indirect labor time (c*) for wild and cultivated resources (table continued, next page). These data do not include adjustments for delay and risk. The following estimates were used: i) where not provided in the source, caloric content of foods (c) is from USDA, Nutrition Data Laboratory: <u>http://www.nal.usda.gov/fnic/foodcomp/search/ index.html</u> from which we have: maize 3650; sorghum (except Cameroun) 3390; millet 3780; rice 3700; ii) farmer storage losses (ten percent) and seed requirements (five percent) so s = 1.17 (see text of this document); iii) a "person day of work" is assumed to be 7 hours unless the source supplies other data; iv) all cultivation output estimates adjusted upwards by 1.079 to simulate greater land abundance (see section S1); v) ratio of edible processed to unprocessed output f = 0.79(7) used for all crops except the ratio of hulled to un-hulled rice (by weight) f = 0.58, and 0.84 for sorghum in Cameroun; vi) processing (hr/kg): maize = 1.73, rice = 1.23, sorghum and millet = 1.09 (see text of this document).

Population (source)	$Comment \\ k \equiv K/H$	с*
Ache (Hill, et al, 1987)(8)	Overall return rate including all food processing time based on 672 person days of foraging: averages of male, 1339; female, 1221(1-0.11) (p. 7,9); (processing of women acquired goods 11% of direct labor time)	1213
Hadza (Vincent 1985(3), Hawkes, et al 1989 and 1991)(16, 29)	Males: Mean of males 1536 (large game); females: 1290 (//ekwa tubers mean of two studies (3, 16) including travel time, with kcal/kg mean from two studies.(3, 30)).	1157
Hiwi (Hurtado and Hill, 1990)(31)	Based on 2798 person days, yearly mean of males:2593 and females 848, which is reduced to 755 deducting 11% for Ache estimated processing costs (p.338.)	1674
Pre-historic Great Basin (Simms, 1987)(32)	Simple average of large and small game (9 species), seeds, roots, and nuts (23 species), estimated for pre-contact Great Basin conditions using (where relevant) experimentally determined processing costs and encounter rates.	2629
Great Basin (Simms, 1987)(32)	Data from a 1917 antelope drive: 1.30 kg/hr including processing, construction and all other times (p.67), correcting a computational error in the source; $c = 1258$ (p 45).	1635

A. Wild resources

B. Cultivated resources

Fremont, U.S. A.D 650-1350 (Barlow, 2002)(10)	"Maximum yields" (12.5 bu/acre, p.78) based on rainfall-estimated returns for modern maize, and minimum hours per acre $(311, p 71)(33)$; k = 1.01	1077
Haute Volta, (Gerardin, 1963)	Tractor and plow use "negligible" draft animals "almost none." Labor input by 'unite de production' with an average of 1.44 individuals per unit (p.64). About 16% is produced for markets (about half of this urban). Entries are for (in order) sorghum, millet, and maize; much lower return ($c^* = 765$) for rice is excluded on grounds that it occupies less than 4% of the labor (and even less of the land); $k = 0.74, 0.58, 1.00$	1082 1037 1073
Cameroun (Guillard, 1965)(28)	Data from 1955-7; $f = 0.84$ (p.245) for 3 types of sorghum over 3 years (in which oxen were not used). Village was part of a "rural modernization" program already "launched on the road to modernization" p.493. So these data may be of dubious relevance; entries are (in order) sorghum, millet; $k = 0.82, 0.73$.	1221 1197
Mexico, (Lewis, 1951)(9)	Tepotzlan, 1944. <i>Tlacolol</i> (hoe) cultivation of maize (p.153); similar returns estimated for plow (and oxen) cultivation not included ; $k = 1.58$	1260
Latin America (Barlow, 2002)(10)	Maize cultivation using "pre-Hispanic" tools and methods (p.72-3) from Peru, Guatemala, and Mexico (including processing estimated by the source author but not accounting for seed requirements and storage losses, accounted for here assuming that $H/(H+P) = .30$, consistent with Mexican data; k = 1.36.	1200
Gambia (Haswell, 1953)(1)	1949 land abundant cultivation "no land hunger in this area;"entries are (in order) early millet, sorghum, rice, and late millet; correction of a computational error in the source (sorghum farm with no labor input in the data); rice data are for swampland only (upland rice yields are extraordinarily low: 57 % of lowland); $k = 0.49, 0.85, 0.65, 0.47$.	927 1172 764 900
Malaysian Borneo (Freeman, 1955)(26)	Iban; open access shifting cultivation of rice, 1952; including the substantial time guarding crops (from pigs, monkeys, p.56-61, 90, 111); $k = 0.78$	848
Malaysian Borneo (Geddes, 1954)(34)	Sarawak, shifting cultivation of wet and dry land rice (averaged) 1949 (p.68); $k = 0.94$.	936

Philippines	Hanunoo (southeast Mindoro) 1952-54: swidden multi-crop cultivation	926
1 mippines	Tranchoo (southeast Windoro) 1952 54, swidden mutit crop curtivation	120
(Conklin, 1957)(4)	using steel axes and knives (p. 58) without animal power (p. 11) "land is a	
	free good" (p. 35); "One man hour of general swidden labor produces among	
	other results 0.77 kg of unhusked rice" (p.152.); counting 45 minutes/hr as	
	rice work and 36 minutes travel time per 7 hour day; $k = 0.92$.	

Table S3. Production work hourly intensity and average daily time by production system

Note: entries are mean (SEE):number of estimates. PAR is the ratio of energy use in the activity in question to the resting energy use. Source: Sackett (1996)(15). Column 1: Tables 7.6 and 7.12 pp. 442, 466; column 2 Table 7.20, p. 485.Working time is the average over all (including non-working) days. Energy use by foragers is weighted by the distribution of times at various foraging activities; similarly energy use for horticulturalists and agriculturalists is weighed by the distribution of farming times. SEE's for the daily input cannot be calculated because the data do not provide the co-variances of the PAR and time.

	energy intensity (PAR) (1)	time (hrs) (2)	daily input (3) = (1)(2)
Foragers	4.1 (0.1): 11	3.7 (1.5):16	15.2
Horticulturalists	3.9 (0.03): 15	4.2 (1.3):35	16.4
Agriculturalists	4.4 (0.1): 11	5.5 (1.2):18	24.2

Table S4. Hypothetical relative returns to cultivating and foraging einkorn. Forager returns are risk adjusted (μ =0.98); no delay adjustment is required as foraging is assumed to be immediate return. Processing time is included in both cases. Reproductive risk adjustment for cultivation is based on a single crop (μ =0.86), using the same data and methods described above. The individual engaging in modest cultivation of einkorn (decision) is assumed to bear no more risk than fully diversified forager. The unadjusted data are c* = 1074 and 1147 respectively for foraging and farming.

	Cultivation returns adjusted for	c* (farmed/foraged)
Decision: (subjective)	Risk (0.98) and delay (0.20)	0.98
Evolution (reproductive)	Risk (0.98, 0.86) and delay (0.02)	0.91

Table S5. Basic data for estimating risk exposure. The first three rows are from the estimated maize yields (kg/ha) in Colorado 600-1300(20); the next two rows are from the sample of Kipsigis women (22).

Variable	Obs	Mean	Std. Dev.	Variance	Min	Max
Annual Data	700	253.8431	45.80961	2098.52	121.4042	401.0497
5 year moving average	696	253.798	28.09106	789.1077	171.7709	330.6964
21 year moving average	680	254.0369	17.60008	309.7628	204.6602	295.0078
Acres per woman	206	17.07194	13.0008	169.0208	1	60
Reproductive success	206	6.800971	2.820517	7.955316	0	13

 Table S6. Alternative data source on risk exposure: wheat yields (quarters/acre) at

 Rimpton manor 1211-1349 (21).

	Obs	Mean	Std.Dev	Variance	Min	Max
Annual	79	1.04	0.360827	0.130196	0.41	2.19
5 year moving average	71	1.037743	0.19655	0.038632	0.56	1.4775
21 year moving average	58	1.037826	0.088574	0.007845	0.864615	1.2125

Table S7. The risk discount for individuals exploiting 1, 2 or 9 species. The main entries are calculated from the data summarized in Table S6. The entries in parentheses are calculated in the same manner, but are based on risk exposure estimates (using the 21 year moving average series) from the medieval English manor of Rimpton (Table S7) rather than the pre contact native American maize farmers. The values of μ used in the calculations reported in the text are (for farmers) 0.92 and (for hunter-gatherers) 0.98.

	m^* (<u>m</u> = 17.07)	μ
One species	14.6807 (13.2821)	0.860032 (0.778098)
Two species	15.7182 (14.6291)	0.920808 (0.857005)
Nine species	16.7334 (16.4074)	0.980279 (0.961184)

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Figure S1.Estimates of seed use as a fraction of gross output (ω), 1211-1978. The earliest estimate is the mean of 3 crops over the period 1211-1268. The latest estimate is the mean of 9 estimates. Source: Table S1.



Figure S2. Twenty-one year smoothed climate-estimated maize yields of pre-contact Americans.



Figure S3 The Fitness function w(m) and the underlying data. The vertical axis is the number of children surviving to age 5 (w) and the horizontal axis is the acres of land farmed by each of the women.

Figure S4. Expected fitness of risk exposed individuals. The horizontal axis is resource availability (acres), the vertical is children surviving to age 5. The dots are each individual's expected fitness given the degree of resource variability estimated as in the text; the solid curve is the expected fitness in the absence of variability. For individuals with more than 25 acres the risk adjustment is insignificant because the fitness function is virtually linear for large values of m.





Figure S5. Estimated distribution of resources: two examples.. The top panel shows the discretized distribution of resources for a woman with the group mean acres (17). The middle and bottom refer to a woman with 8 acres whose resource shocks we model by shifting the distribution to the left (from mean 17 to mean 8) and then reassigning to m = 0.02 all realizations that fall below that minimum resource level.