A quantitative analysis of intensification in the ethnographic record.

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March 3, 2021

Abstract. The intensification of food production plays a central role in the evolution of complex human societies. However, it is unclear if the standard model of intensification is theoretically or empirically justified. This leaves social scientists unable to make reasonable inferences about the relationship between intensification and the evolution of social complexity in past societies. To remedy this problem, I derive a novel model of intensification from human macroecology, settlement scaling theory, human behavioral ecology, cultural evolutionary theory, and niche construction theory. The standard and cultural niche construction models are formalized and their predictions are tested using a comprehensive ethnographic data set that describes food production in forty human societies ranging in complexity from foraging bands to agricultural states. Analysis of the ethnographic record suggests we reject the standard model and tentatively accept the cultural niche construction model. I attempt to demonstrate the broader utility of the cultural niche construction model as a framework that may help explain the transition from small-scale to large-scale complex societies.

Main. The intensification of food production has been modeled in two ways in social evolutionary theory. In classical theory, technological innovation reduces the labor required for food production which, in turn, leads to the division of labor, population growth, and the evolution of social complexity [1–6]. In the standard model of contemporary theory, intensification is argued to be an increasingly labor-intensive process necessitated by population growth and political exploitation [7–20]. Ethnographic data has been used to challenge [21–24] or support [25–33] the standard model but no comprehensive analysis the ethnographic record has been undertaken. (A detailed intellectual history of the intensification literature is provided in SI Text.) This lack of consensus is a grave problem for social scientists whose inferences about the relationships between innovation, labor productivity, intensification, and the evolution of social complexity in past societies are valid only to the extent to which adequate ethnographic evidence exists.

This paper seeks to resolve this problem and advance our theoretical and empirical knowledge of intensification. I derive a new model of intensification—the cultural niche construction model—that synthesizes theory and data from human macroecology, settlement scaling theory, human behavioral ecology, cultural evolutionary theory, and niche construction theory. I then formalize and test the predictions of the standard and cultural niche construction models using a comprehensive quantitative data set that describes food production in forty ethnographically-known societies ranging in complexity from foraging bands to agricultural states (Table 1; Materials and Methods). The ethnographic record provides no support for the standard model and suggests we tentatively accept the cultural niche construction model. In the discussion section, I demonstrate the broader utility of the cultural niche construction model as a mechanism-based, mathematical framework that may further our understanding of evolution of large-scale complex societies.

The standard model. The first assumption of the standard model is that more intensive systems are less productive per unit of energy input, E_{in} . Let the labor productivity P of

a food production system at a given technological level ϵ be defined as the mean ratio of energy output, E_{out} , to E_h , the fraction of E_{in} derived solely from human labor:

$$P_\epsilon = \langle \frac{E_{out}}{E_h} \rangle \quad (1)$$

The first prediction of the standard model can be stated as the following inequality:

$$P_\epsilon > P_{\epsilon+k} \quad (2)$$

where k indexes progressively more intensive systems. The second assumption of the standard model is what is known in economics as the “law of diminishing marginal returns” to food producing labor. The law states that any single-input food production function is characterized by decreasing then negative marginal returns [34–36]. We can formalize the marginal returns to energy input as a linear relationship and the production function as its integral, a second-order polynomial. The second prediction of the standard model can be formally stated as

$$\frac{dE_{out}}{dE_{in}} = b - 2aE_{in} \quad (3)$$

$$E_{out} = bE_{in} - aE_{in}^2 + \epsilon \quad (4)$$

where ϵ is a constant that describes the technological and institutional context in which food production takes place and a and b describe how E_{in} and E_{out} are marginally related. The behavior that follows from this model is that rational food producers will increase input until the maximum output in a given context is achieved; once output begins to fall, producers will invent or adopt technologies that allow for intensification while sacrificing labor productivity (Figure 1).

The cultural niche construction model. Two hallmarks of social evolution are urbanization and the division of labor. As the populations of settlements and cities within complex societies grow, they are divided into an increasingly large array of professional and organizational roles, all of which must be fed by an increasingly small number of food producers [37–41]. The rates of urbanization in the earliest states in Mesopotamia, Egypt, the Indus Valley, China, Mesoamerica, and the Andes range from ~ 30 to 95% [42] and archaeological evidence suggests that a variety of intensive agricultural technologies were used at this time [31, 43–47]. This suggests that cross-cultural agricultural labor productivity ~ 5500 –1500 years ago was already reaching relatively modern levels [48]. The first prediction of the cultural niche construction model follows from the empirical observation that labor productivity appears to increase as food production technologies and politically organized cities develop:

$$P_\epsilon < P_{\epsilon+k} \quad (5)$$

The second prediction of the cultural niche construction model derives from the sublinear scaling of area with population, such that $A = aN^\alpha$ where a is a normalization constant and α is a scaling exponent less than 1 that describes how area and population are marginally related [49, 50]. Spatial equilibrium results from balancing the costs of moving people, materials, and information over a given area with the benefits of social interaction and exchange among individuals and with the environment [50–52]. The cost of movement

over a distance L can be expressed as cL where c is the energetic cost per unit length in a given technological and institutional context. Any given area—whether organized as a hunter-gatherer territory, an agricultural state, or a modern city—is characterized by an infrastructural network that facilitates interaction between all members of a population. If we assume that the distribution of a population N over a given area A is density-dependent, then, on average, every member of the population will occupy a unit of area (A/N) and require $(A/N)^{1/2}$ units of infrastructure to insure connection with the rest of the population. The total length of the network $L_n = N(A/N)^{1/2} = aN^\beta$, where $A = aN^\alpha$ and $\beta = (1+\alpha)/2$ [50, 52, 53]. By multiplying the length of the infrastructural network L_n by the cost of movement c we obtain the energetic cost of social life in a given area:

$$E = \epsilon N^\beta \quad (6)$$

where ϵ describes the technological and institutional context that mediates between energetic costs and benefits, E is total energy output, N is population size, and β describes how population and the infrastructural network are marginally related.

This simple model of population-level energy use allows for the derivation of an individual-level (food) energy production function. We can think of the left hand side of Equation 6 as the total energy output or consumed by a given population and the right hand side as representing the energy input required to generate this level of output. On the left hand side, E can be rewritten as the size of the population multiplied by the average energy output per person ($N(\frac{E_{out}}{N})$). On the right hand side, N can be rewritten as the size of the population multiplied by the average energy input per person ($N(\frac{E_{in}}{N})$). These substitutions lead to the following equation

$$N(\frac{E_{out}}{N}) = \epsilon(N(\frac{E_{in}}{N}))^\beta \quad (7)$$

which simplifies to the second prediction of the macroecological model:

$$E_{out} = \epsilon E_{in}^\beta \quad (8)$$

where ϵ is a constant that describes the technological and institutional context in which food production occurs and β describes how energy input and output are marginally related. The societies described in the *Ethnographic Atlas* are characterized by an α value of approximately 1/2 [49] so we predict a β value for food production in the ethnographic record close to 3/4. The behavior predicted by the cultural niche construction model derives from principles of cultural evolutionary theory, niche construction theory, and human behavioral ecology acting in concert under the constraint of sublinear marginal returns imposed by Equation 8. Cultural niche construction theory predicts that energy output will be maximized by human societies [54] while the principle of net energy maximization of human behavioral ecology predicts that individuals will minimize the energy input required to achieve a given level of output [55, 56]. The only means to achieve these goals simultaneously is a continual process of niche construction and technological innovation that increases output and labor productivity (Figure 1).

Results. Foraging, extensive, intensive, and early industrial food production technologies produce .01, 7, 14, and 15 gigajoules per hectare per year, on average. The labor productivity values associated with these technologies are 10, 30, 53, and 125 units of energy output per unit of human energy input. Thus, labor productivity increases with intensification (Figure 2). The standard model fails to predict the relationship between energy input and

output or the behavior of ϵ as food production is intensified. The cultural niche construction model accurately predicts the marginal relationship between energy input and output, the behavior of ϵ as food production is intensified, and the value of β . A multiple linear regression of the logarithm of energy output on the logarithm of energy input and food production technology has a slope of $\beta = .76$ and explains over 95% of variation in output (Table 2). The intensification of food production in the ethnographic record is accurately described by the cultural niche construction model. This analysis strongly suggests we reject the standard model.

Discussion. There are, broadly speaking, two traditions of social evolutionary theory in which intensification plays a central role (see SI Text). The classical and contemporary models of intensification are, however, flawed and it is unclear if inferences based on these models about the relationships between innovation, intensification, population growth, and social evolution in past societies are reasonably justified. In other words, there are large-scale patterns in the ethnographic, archaeological, and historical records that are not adequately explained by current theory. In enlightenment and liberal evolutionary theories, technological innovation allows for a reduction in the amount of labor required for food production which, in turn, allows for intensification, population growth, and the development of social complexity in a strictly linear process. The empirical claim of increasing labor productivity is justified by the ethnographic record but the classical model lacks a mechanistic framework that explains how or why innovation should take place at all, much less how innovation rates ought to vary as large-scale complex societies develop. Similar problems plague the romantic, Marxist, and postmodern tradition in which it is incorrectly assumed that intensification is an increasingly labor-intensive process. More problematic is the standard model’s causal framework in which population growth and social complexity exist prior to and cause the development of more intensive food production. While it is reasonable to assume that large-scale, densely-populated, complex societies will have advantages in creating new food production technologies, it is unclear how or why social complexity can or ought to develop under initial conditions of perpetual food scarcity and winner-take-all exploitation. Both the classical and contemporary models make important contributions to our understanding of intensification but need to be synthesized with the ethnographic data compiled here and the social scientific principles that underpin the cultural niche construction model.

The theory and data presented here provide a mechanistic and mathematical framework with which social scientists can make reasonable inferences about the dynamic cross-cultural process which links innovation, intensification, population growth, and the evolution of large-scale complex societies (Figure 3). The process outlined in Figure 3 gives causal primacy to the processes of cultural evolution and niche construction, or what has been termed “cultural niche construction” [54]. Cultural niche construction recognizes the primary role played by the evolved capacity to acquire, comprehend, and transmit knowledge about what Odling-Smee and colleagues [57] refer to as the “casual texture” of the biotic and abiotic environment. The development of technologies, knowledge, and norms used to manage the biotic and abiotic environment are found universally [24, 27, 33, 58, 59] and variation in these cultural practices directly effect the productivity of labor and land. Innovations in food production technology and norms that increase the intensity of food production and labor productivity are selected for at two levels: (1) at the individual level, where the principle of net energy maximization dictates that more productive technologies will be adopted; and, (2) at the population level, where intergroup competition will, through a variety of mechanisms, tend to select for cultural traits of larger populations[60, 61], as the systematic

and global spread of farming cultures since the Neolithic illustrates [62, 63].

Here I focus on one iteration of the process of intensification, the transition from foraging to traditional farming. There is no reason to assume that past changes in land use, labor productivity, and population cannot be modeled using the ethnographic data reported here and in the *Ethnographic Atlas* [64]. Although we must recognize that contemporary foragers occupy more marginal lands than was the case thousands of years ago and that the traditional farming of the ethnographic record is likely more productive than its ancestor practices, correcting for these errors (work for future research) is very unlikely to alter the basic patterns documented here. Using this data we can reasonably infer that the transition from foraging to traditional farming led, on average, to a four-fold increase in labor productivity, a forty-fold increase in energy output, a thousand-fold increase in the intensity of food production, and a four-fold increase in population. In the archaeological record, the high rate of population growth that followed the transition from foraging to farming is known as the neolithic demographic transition [65, 66]. The neolithic demographic transition is hypothesized to have resulted from the increased fertility associated with the reduction in labor required for food production and the decreased mortality associated with a growth in the food supply (energy output). This mechanism can likely be generalized to any energy transition in which carrying capacity grows more quickly than population [67, 68].

The results of this paper provide empirical data that supports the hypothetical mechanisms proposed by scholars studying the neolithic demographic transition (and subsequent transitions). In addition to population growth, the the transition from foraging to farming also allowed for (1) an increase in population density, sedentary settlement, and urbanization, as the land use required for food production decreased by orders of magnitude; and, (2) the division of labor, as, on average, the work required for food production decreased from over 4 hours per day per person (Table 3) to roughly 1 hour per day person. The development of increasingly large, dense, and economically-specialized populations living in urban settlements required the development of political organization to facilitate cooperation between large numbers of genetically and culturally unrelated individuals and groups [42, 69].

So far, this model of social evolution has proceeded along the tracks of the enlightenment and liberal model to its end point. And here we must fuse the classical model of intensification with the standard model's insight that large, dense populations have advantages in creating new food production technologies which feedback into the basal process of cultural niche construction. Politically-organized urban populations exhibit increasing returns to scale in terms of rates of technological innovation [70, 71]. In other words, the rate of technological innovation in politically-organized settlements and cities begins to grow more quickly than population meaning that the division of labor and carrying capacity also grow more quickly than population. This property of politically-organized settlements and cities creates a virtuous circle of increasing innovation, intensification, population growth, and economic and political complexity, and is likely only one instance of the exploitation of positive feedback mechanisms which seem to be a general property of the process of cultural niche construction [72–74].

Table 2. Regression results.

standard model	sample size	coefficients			variation explained
	n	a	b	ϵ	r^2
foraging	204	-.021	6.0	3.2	.56
swidden	215	-.002	27.8	-455	.68
intensive	86	.007	-41.0	67440.0	.87
early industrial	16	-.005	214.2	-219800.0	.65
multiple linear model	520	.002	13.7	2173	.93
macroecological model	sample size	intercept	slope	95% C.I.	
	n	ϵ	β		r^2
foraging	204	6.45	.75	[0.60, 0.91]	.31
swidden	215	83.9	.79	[0.73, 0.84]	.76
intensive	86	366.3	.63	[0.45, 0.81]	.36
early industrial	16	1228.0	.75	[0.43, 1.08]	.62
multiple linear model	520	98.5	.76	[0.68, 0.83]	.95

Figure 1. The standard and macroecological models illustrated. In the standard model, food producers increase energy input until the maximum output in a given technological and institutional context is achieved; once output begins to fall producers will invent or adopt technologies that allow for intensification while sacrificing labor productivity. In the macroecological model, food producers continually engage in niche construction and technological innovation to maximize output and labor productivity.

Figure 2. The intensity of food production and the productivity of human labor in different technological and institutional contexts. The blue dots represent the average tendencies in the data. Note that while intensity increases linearly, labor productivity increases linearly in log transform. This implies that labor productivity grows exponentially with technologically and institutionally induced intensification.

Figure 3 illustrates the mechanisms and mathematics of the dynamics of the cultural niche construction model. This illustration assumes that the basal process of cultural niche construction and technological innovation only affects ϵ , although clearly technologies and norms also change the values of a , α , and β . As food producers acquire and transmit knowledge of their biotic and abiotic environment, innovations in food production technologies and norms are introduced that increase the values of ϵ and E while decreasing the value of A . This intensification of food production increases labor productivity and the overall food supply in a given area, which increases population by increasing fertility and decreasing mortality. As human populations become large, dense, and sedentary, political institutions must develop in order to overcome the centrifugal forces of scalar stress and facilitate cooperation among genetically and culturally unrelated groups. The rates of technological innovation in populations of politically-organized settlements and cities grow faster than the populations themselves, and this feeds back into the basal process of cultural niche construction. The process, once the barriers to its first iteration are overcome, is autocatalytic.

Materials and methods. The data set analyzed in this paper describes food production in forty human societies ranging in sociopolitical complexity from foraging groups to agricultural states. This data was collected from primary ethnographic sources in which food production was studied over a given amount of time and area. The criteria for inclusion in the data set were that the technology, intensity, energy input, energy output, and area were recorded or calculable. More specifically, the criteria for inclusion in the data set were that: (1) the food production technology (e.g., foraging, extensive, intensive, or early industrial) was clearly identified; (2) the amount of labor (human, animal, and/or machine) was recorded in units of time or energy; (3) the food output was reported by volume, weight,

Table 1. Primary ethnographic data sources.

primary ethnographic source	geographic location	ethnolinguistic group, community, or nationality
Geddes [75]	Borneo	Bidayuh / Land Dayaks
Freeman [76]	Borneo	Iban / Sea Dayaks
Conklin [77]	Phillippines	Hanuoo
Moerman [78]	Thailand	Shan
Durrenberger [79]	Thailand	Shan
Durrenberger [80]	Thailand	Lisu
Barker et al. [81]	Burma, Thailand, Japan, Taiwan, Java	Burmese, Thai, Japanese, Taiwanese, Javanese
International Rice Research Institute [82]	Philippines	Philillino
Janlekha [83]	Thailand	Bangchan, Thailand
Conelly [84]	Phillipines	Napsaan
Chin [85]	Malaysia	Kenyah
Cramb [86]	Malaysia	Iban
Hastorf [87]	Peru	Peruvian
Carter [88]	Guatamala	Kekchi Maya
Truman [89]	Guatamala	Cantel, Guatamala
Kirkby [90]	Mexico	Oaxaca, Mexico
Lewis [91]	Mexico	Tepoztlan, Mexico
Tax [92]	Mexico	Panajachel, Mexico
Cancian [93]	Mexico	Zinacantan, Mexico
Logan and Sanders [30]	Mexico	The Basin of Mexico
Stadelman [94]	Guatamala	Huehuetenango, Guatamala
Steggerda [95]	Mexico	Yucatec Maya
Kelly and Palerm [96]	Mexico	Tajin Totonac
Rappoport [97]	New Guinea	Tsembaga
Grimes [98]	United States	American
Cane [99]	Australia	Gugadja/Pintubi
Couture, Ricks, and Housley [100]	United States	Harney Valley Paiute
Winterhalder [55]	Ontario, Canada	Cree
Noss [101]	Central African Republic	BaAka
Hawkes et al. [102]	Tanzania	Hadza
Lupo and Schmitt [103]	Central African Republic	Bofi / Aka
Bliege Bird and Bird [104]	Australia	Martu
O’Connell and Hawkes [105]	Australia	Alyawara
Greaves [106]	Venezuela	Pume
Eder [107]	Phillippines	Batak
O’Connell and Hawkes [108]	Australia	Alyawara
Blurton Jones, Hawkes, and Draper [109]	Nambibia/Botswana	!Kung San

Table 3. Hours per day spent producing food among foragers.

source	hours per day	ethnolinguistic group
Lee [112]	3.0	!Kung San
Hames [113]	2.0	Yanomamo
Hawkes, Hill, O’Connell [114]	4.2	Ache
Ichikawa [115]	7.3	Mawanbo
Terashima [116]	8.3	Bambote
Terashima [117]	5.2	Mbuti
Arsdale [118]	1.5	Asmat
Hawkes et al. [21]	3.8	Northern Ache
Mean hours per day foraging	4.4	

or caloric value; and (4) the area of land used for food production was recorded or, in the case of foragers, was available from other sources. 520 food production case studies in 40 societies described in the ethnographic record met these criteria. While the data set is, to my knowledge, exhaustive with respect to the criteria outlined above, there are many dimensions of possible variation that the data sources do not record and are therefore not accounted for by the analyses performed here. The inclusion of data that describe sedentary foragers in extremely productive environments, farmers from highly arid environments with weak property rights, or low-level food producers who practice mixed foraging-farming strategies would all, assumably, have appreciable effects on the analyses. The crops represented in farming data set are also largely limited to maize, rice, and wheat, though sweet potatoes, taro, and sugar cane are also in the sample. The lack of data on non-grain staple crops introduces another potential bias in the data.

Intensity was operationalized as energy output per unit area of land per unit time [110] and reported in gigajoules per hectare per year in the body of the paper but reported in MJ/ha/year in the SI data set. Because the vast majority of forager food production cases were daily in temporal scope and undertaken by individuals, the following calculations were made to make the data comparable to farmer data. E_{out} for a given day of foraging was calculated by assuming an 4.3 hour day (see Table 2) and multiplied by 365. For example, if a forager is recorded as producing 1 MJ/h, $E_{out} = 1 \text{ MJ/hour/person} \times 4.3 \text{ hours/day} \times 365 \text{ days/year} = 1569.6 \text{ MJ/person/year}$. This figure was then divided by the area per person in a given territory (the inverse of population density for a given ethnolinguistic group) A/N , taken from Binford’s hunter-gatherer data set [111]. This resulted in a figure with the dimensions of annual power density, MJ/ha/year.

The methods for calculating energy input and output for the case studies is detailed below. The proxy used to measure energy input E_{in} is the amount of human, animal, and/or machine labor expended to produce food. For farmers, this quantity is usually reported in the ethnographic sources in “man-days.” In order to make the foraging and farming data comparable, I converted all “man-days” to 6.5 “man-hours” and all “man-hours” to moderate person-hours of work (see Table 3; refs. [119, 120] also report a 6.5 hour day among modern Mexican and Central American laborers). Smil [ref. [33], p. 60] estimates that an average person-hour of work is equivalent to 0.8 MJ. The energy expended to produce food by h hours of human labor was calculated as:

$$E_{in} = h \cdot 0.8 \text{MJh}^{-1} \quad (9)$$

Table 4. Hours per food producing workday among farmers.

source	hours per day	ethnolinguistic group or community
Baldwin [121]	7.7	Nupe (Niger Valley)
Stone et al. [122]	4.4	Kofyar (Nigeria)
Painter-Brick [123]	5.3	Tamang (Nepal)
Clark [124]	8.2	Britian (1800s)
Pospisil [125]	8.0	Kapauku (New Guinea)
Slicher van Bath [126]	6.0	England (1200s)
Goodell [127]	8.0	Rahmat-Abad village, Iran (1972/3)
Cleave [128]	4.8	Africa (1900s)
Clark and Haswell [26]	6.5	Africa and Asia (1900s)
Mean hours per day farming	6.5	

This measure of energy input E_{in} is robust to variation among persons and between groups and ought to have cross-cultural applicability.

Similar calculations were made to account for non-human energetic input. The use of oxen, water buffalo, and horses in food production are reported in the ethnographic sources. These animals expend, on average, 1.44 MJh^{-1} , 1.44 MJh^{-1} , and 2.34 MJh^{-1} , respectively [ref. [33], p. 67]. The number of these animals and the quantity of time or the exact tasks they are used for are detailed in the sources. However, in one case [79] the time over which the buffalo were used had to be estimated at 40% of the agricultural season [ref. [33], p. 65]. In the case of early industrial wheat production in Kansas in the early 1920s [98], the tractor make and model had to be inferred from what was produced and available to farmers in that region at the time and its power rating was taken from a study conducted by the Department of Agriculture, University of Nebraska–Lincoln (available at <https://digitalcommons.unl.edu/tractormuseumlit/623/>). Although animal and machine input are non-human in origin, they are measured in the common currency of energy and—from the food production system’s point of view—are indistinguishable from human input.

Measuring the energy output E_{out} of the food production system is generally more straightforward. In the case of plant cultivation the energetic output was reported as the volume, weight, or caloric value of a given weight of food. These measurements came in an array of indigenous metrics all of which were converted to kilograms of food. This weight was then multiplied by the foods’s gravimetric energy density. The same approach was used in the case of hunting and foraging output. The energetic output of the food production system was measured as

$$E_{out,i} = \text{kg resource}_i \cdot \text{gravimetric energy density of resource}_i (\text{MJ/kg}) \quad (10)$$

Below, I provide the reader with two examples of how the raw data was converted into the energy input and energy output data recorded. Barker et al.[81] report intensive rice farming data for several countries. The energy input is reported in man-days per hectare and buffalo-days per hectare. Both of these figures were multiplied by 6.5 hours/day to obtain man-hours/ha and buffalo-hours/ha. The man-hours were multiplied by .8 MJ/hour and the buffalo-hours were multiplied by 1.33 MJ/hour; these figures were summed (MJ/ha) and multiplied by the number of hectares to arrive at the energy input figure (MJ). The energy output was reported as kilograms of rice per hectare. This figure (kg rice/ha) was

multiplied by 14.9 MJ/kg rice and the number of hectares over which it was grown to arrive at an energy output figure in MJ. Cane [99] reports energy input and output data for Gugadja foragers. The energy input was reported in man-minutes which was multiplied by 60 min/hour and .8 MJ/person-hour to arrive at a figure in MJ. The energy output was reported in kilocalories which was multiplied by 0.004184 MJ/kcal to obtain energy output in MJ.

The rates of urbanization in early states were calculated using the Supplementary Data given by Sandeford [42]. These data measure either the population or the area of settlements within a given polity and are sorted hierarchically into tiers based on the modal distribution of settlement sizes. Urbanization was calculated as the percentage of the population living in capital cities and regional centers (tiers 1 and 2 of the settlement distributions). As many of these estimates are based solely on area, they tend to underestimate the population living in larger settlements and the overall rates of urbanization [129].

The rate of population growth reported in the Discussion for the *Ethnographic Atlas* [64] was calculated by regressing the average population value at a given level of intensity on the index of intensity (variable 28) where this index is an ordinal scale ranging from 1 indicating no agriculture to 7 indicating intensive irrigated agriculture. As intensity is intended to be an ordinal scale I changed the value of horticulture from 4 to 2 but otherwise left the order preserved.

All statistical analyses were done in R. The regressions performed to test the fit of the standard model were ordinary least-squares linear models of E_{out} on E_{in} using the *poly* function to transform E_{in} . The regressions performed to test to fit of the macroecological model were ordinary least-squares linear regressions of the log-transformed values of E_{out} on E_{in} . The multiple linear regression models used the same transformations outlined above but added technological and institutional context ϵ to the input as a factor. That is, energy output E_{out} was regressed on energy input E_{in} and technological and institutional context ϵ .

Acknowledgments. I thank Matthew Peeples, Christopher Morehart, Micheal E. Smith, José Lobo, Billie L. Turner II, and for their invaluable help in researching, conceptualizing, writing this paper. I am also heavily indebted to three anonymous reviewers for vastly improving the published end product of this work.

Supplementary Information Text. Intellectual history of intensification in the social science literature.

There are, broadly speaking, two traditions in social evolutionary theory. In the classical tradition—deriving from enlightenment and liberal thought—influential figures such as White [4], Childe [5], and Adams [6] argued that intensification was associated with a significant reduction in the labor required for food production which, in turn, led to the hallmarks of complex societies such as an increasing division of labor, technological innovation, and population growth, all of which were interlinked in a process of continuous material progress. This view was challenged in the mid-late twentieth century as political, demographic, and ecological concerns profoundly changed social scientists’ attitudes toward state-level social organization, economic development, and modern technology [17, 130]. The social evolutionary theory formulated in this context [16–19] reflected these concerns and was heavily influenced by German romanticism, Marxism, and postmodernism [131, 132]. As Bruce Trigger (ref. [133], p. 411) writes, a new theoretical paradigm emerged in which intensification was viewed as having “compelled most people to work harder, suffer increasing exploitation, and degrade their environments.” The contemporary theoretical consensus

that intensification is an increasingly labor-intensive process necessitated by population pressure or political demands for surplus production was originally articulated by Wittfogel [7]—who was heavily influenced by Weber and Marx—and solidified over the course of the 1960s by a number of prominent social scientists [8, 10–13].

The work of Danish economist Ester Boserup [9, 70] became extremely influential in this context. It articulated the mid-twentieth century theoretical consensus in the form of a simple, parsimonious, evolutionary model of the relationship between agricultural intensity, population, and sociopolitical complexity. Boserup argued that growth in population and sociopolitical complexity necessitated intensification which, in most cases, required the invention or adoption of more labor-intensive technologies. Her work thus allowed social scientists to create powerful mechanism-based, deductive, cross-cultural models of the evolution of human societies, often with very limited data (e.g., evidence of population growth and the development of a settlement hierarchy). The appeal of such a model is difficult to overstate.

The empirical validity of the standard model, however, remained contested. It has been supported or challenged using a variety ethnographic data but no comprehensive analysis the ethnographic record has been undertaken. Hawkes *et al.* [21] and Piperno and Pearsall [22] find that labor productivity increases as the transition from foraging to farming is made among the Machiguenga, Yanomamö, and Aché of the Amazon. Bowles [25] uses cross-cultural historical and ethnographic data to model the productivity of foraging and early farming and argues early farming required more labor. Clark and Haswell [26], Netting [27], Kirch [28], and Stone [29] find evidence for the standard model in African and Polynesian case studies. Sanders [30, 31] uses ethnoarchaeological data to study the transition from swidden to plow, irrigated, and raised-field agriculture in ancient Mesoamerica. Although he was an exponent of the standard model, his data show that intensification is in every case associated with increased labor productivity. Using cross-cultural historical and ethnographic data, Bronson [23] concludes that more intensive forms of farming are universally associated with higher labor productivity. Hunt [24] uses ethnographic data to compare the labor productivity of traditional swidden and irrigated rice farming in southeast Asia and finds higher productivity among the more intensive systems. Smil's [33] global account of the emergence and intensification of agriculture relies on reconstructions of labor productivity based on historical and ethnographic sources and lends support to the standard model.

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