Pre-Guns, Pre-Germs, Pre-Steel: Geography and Agriculture as the Source of Inequality

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Wealth is unequally distributed both within a country, and between countries. If the worlds cash was to be equally distributed among the entire world population, it would amount to a mere $34,000 per person. In reality, half of the worlds population hold less than one tenth that amount, while the vast majority is concentrated in the hands of a very few. In fact, the richest five percent hold over 70 percent of the wealth [2]. Understanding the historical and ongoing causes for such uneven distribution of resources is key for dealing with issues such as world poverty, and for establishing priorities for development aid [3].

Consequently, reasons for the inequality of the wealth of nations have been the subject of extensive study and debate, going back to at least the XIX century. Most modern research has ascribed regional differences in wealth on the consequences of colonialism, and ongoing economic and political processes [1]. Although this line of reasoning has its advantages, such as being able to draw on current macro- and microeconomic indicators, it fails to consider long-term historical autocorrelations, and it overlooks questions of why colonialism occurred at all – why Europe was able to colonize the rest of the world rather than another region.

In contrast to explanations rooted in recent history, in his book *Guns, Germs and Steel*, J. Diamond focused on the latent effects of pre-history. Diamonds thesis centers around the assumption that the roots of present-day economic inequality have been set before the origin of agriculture, by the chance availability of resources and the relative placement and connectivity of geographic land masses. In his view, the rise of agriculture, where it was successful, has led to the development of cities, complex social infrastructure, and ultimately technology (such as guns), which enabled the most developed societies to colonize others. In particular, geography played an explicit role in Diamonds argument, as he suggested that technology may have developed most rapidly in regions with moderate connectedness [Europe], neither too high [China], nor too low [India].

Diamond's (1997) argument that geographic topology played a central role in the timing and development of variable settlement and civilization sizes presents a testable hypothesis using agent based simulation. However, modeling such a phenomenon requires some simplifying assumptions about the productivity of global landscapes at the times of population dispersal and settlement and about the nature of human behavior that drives such dispersals. Regarding the first set of assumptions, the approximately 180,000 years in which anatomically modern Homo sapiens have inhabited our planet has witnessed significant climatic changes, which had profound effects on critical resource distributions [citations].

To try to account for all of the paleohistorical resource variability across the globe over such a time depth and at a scale that is relevant to individual or population-level human behavior presents a Herculean task that is unlikely to be realized in our lifetime. In the meantime, our model assumes that bioproductivity provides a reasonable measure of limiting resource productivity–namely, calories. The relatively recent availability of satellite data, high-resolution spatial ecological analyses a global, and web-based data distribution makes such data readily appliable. We use modern bioproductivity data, which has a resolution of XX degrees [6, 7]. Although we acknowledge that bioproductivity has changed dramatically during the time-frame of interest, it is not the bioproductivity values per se that is of interest to the model. Rather, the model operates on the spatially relative values of bioproductivity, and we assume that at some level, the relative values are constant over time.

Nor, in a linear sense, can bioproductivity itself cannot be considered a reasonable proxy for caloric resource abundance [4, 8]. Human biological evolution has largely taken place in African Savanahs and scrublands where large game, weedy plants, and nuts provide the bulk of human calories. As one moves into increasingly productive jungle zones and decreasingly productive desert and tundra zones, the amount of edible biomass decreases. Because Savanah bioproductivity lies to the right of the global median for bioproductivty, we assume caloric production is actually a non-linear, non-monotonic, function of underlying bioproductivity, which takes the form

$$C_i \propto BP_i - \alpha \frac{BP_i^2}{\max_i BP_i}, \tag{1}$$

where C_i is the extractable caloric production at patch i and BP_i is the underlying bioproductivity, and $\max_i BP_i$ is the maximum value of bioproductivity in the dataset (for our dataset, this is 1155.607 *units.* This gives a peak production at

$$BP_{peak} = \frac{1}{2} \frac{\max_i BP_i}{\alpha},$$

showing that α is a fitting parameter for fine-tuning the caloric production model. By taking $\alpha = 1.05$, therefore, the most productive zones in terms of edible biomass are assumed to lie between approximately X and Y C/ha, shown in Fig. 1 When hunter-gatheres extract resources from their local environment, they must also expend calories in the extraction process. High-density foliage and swamp-land may indicate high bioproductivity, but they are also regions with some of the lowest population density[1] Thus, we have chosen Eq. **??** to represent the lack of net-extractable calories in the extremes of the bioproductivity scale.

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[1] In fact. in summer, 2008, over 125,000 western lowland gorillas were discovered in the Congo, in an area that had been impenetrable by humans until now. There also still remain tribes in the Amazon that have not had any contact with modern civilization.

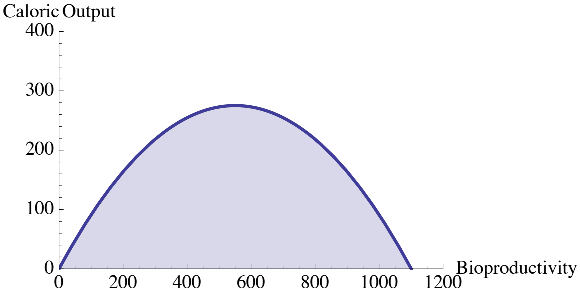

Figure 1: Because raw bioproductivity is only a measure of carbon production, it does not report the amount of net-extractable calories. Low productivity and high productivity regions require extra effort to search for small amounts of edible biomass. Hence, we have mapped bioproductivity into caloric output, which as arbitrary units, using Eq. 1.

Our agent based approach is particularly well suited to testing Diamond's hypothesis because it draws upon the actions of individuals and populations of individuals in a dynamic environmental and social landscape. As a theoretical approach to predicting hunter-gatherer and early agricultural human settlement and subsistence behavior, optimal foraging theory has enjoyed a significant degree of success [5, 9]. Optimal foraging theory is the subset of human behavioral ecology and evolutionary ecology that posits caloric optimization behaviors amongst human individuals and populations. Such models are average-rate maximizing and take some form of C.S. Holling's disc equation [10], which can be expressed as follows:

$$R = \frac{(\lambda * e - s)}{(\lambda * h + 1)},$$

where R is the return rate, λ is a prey encounter rate, e is the cost per unit of search time s, and h is the average handling time of the prey.

Our discussion draws upon three optimal foraging models–the patch choice, ideal-free distribution, and prey choice models. The patch choice model accounts for the fact that resources are heterogeneously distributed in space and offers a method for predicting which patches organisms will occupy [10]. It predicts that they will exploit those patches that maximize caloric return rates after taking into account the cost of travel between patches. The marginal value theorem, when applied to this model, requires that an organism will relocate to a new patch when it has depleted the resources on its current patch to the point that the net gains from an alternative patch exceeds the current gains from the occupied patch. This model provides a critical starting point for our agent based model, which seeks to simulate how populations move through geographic space. In our model, a seed of randomly placed human-population agents are programmed to seek out optimal caloric resource patches and to move to new patches in accordance with the patch choice model. Our agents demonstrate satisficing behavior; if the current patch sustains them, they do not risk moving to a new patch, even it is much more productive. Patch size on our world map are so large as to prevent an agent from casually exploring neighboring areas. Moving one patch, which could represent a sojurn of hundreds of miles, is one that is taken out of necessity. As long as the populations satisfy the caloric needs of their respective populations, they will reproduce and grow. The mother and daughter agents must now share the resources on the patch, which may no longer be enough to sustain the two of them.

In this case, they seek out better patches.

For hunter-gatherers, who extract resources from nature as available, caloric production must be shared equally among all agents occupying their patch. A patch that sustained its occupants may become over-exploited by birth or migration of new agents. When searching out new homes, agents must not just find patches with suitable base caloric production. They must move into new patches that are not already fully utilized by others.

But what happens when an agent is confronted with no alternative patch because the landscape is full and/or alternative patches are simply less productive? Barring no other solution, the populations would fall into an equilibrium wherein death rates would equal birth rates, and population levels would stabilize at the patches' carrying capacities. However, we know that human populations do not behave like this; communities can relieve population pressure through fissioning and colonization of less productive zones. The ideal-free distribution model predicts that when the highest ranked patch falls below the level of the next highest ranked patch, population members occupying the first patch should colonize the second. In turn, the population at the second ranked patch will grow until the resources are depleted to the level of the third ranked patch at which time colonists will occupy it, and so-on-and-so-forth. Although population may initially grow exponentially, as shown in Fig. 2 as agents exploit available resources, when they saturate their locale, population can only grow as fast new patches are discovered via long range exploration. Eventually, hunter-gatherers reach a sustainable level where population is dominated by stochastic factors such as weather events and prey population dynamics. To this point, the models all assume that resource productivity is constant. However, coevolutionary processes such as the domestication of plant and animal species are an important component of human population dynamics and a critical component in Diamond's model. Diamond argues that the when and where of domestication is a historical accident. Certain species are simply more conducive to domestication because of their temperaments and social behaviors. Accordingly, our model draws from current archaeological knowledge of the geographic origin loci for the world's known prehistoric domesticates, which includes:

1. barley, wheat, lentils, sheep, goats, cattle, and pigs from the fertile crescent region of the Near East,
2. rice and cattle from the Yellow and Yangtze regions of China,
3. African rice, sorghum, and perl millet from sub-Shaharan Africa,
4. maize, beans, and squash from Central America,
5. quinoa, potatoes,alpaca, llama, and guinea pigs from the Andean highlands, and
6. chenopodium, sunflower, and marsh elder from eastern North America [12].

A common misconception about agricultural origins is that our hunter-gatherer ancestors would have naturally tended toward domestication as a superior economic alternative to hunting and gathering. However,

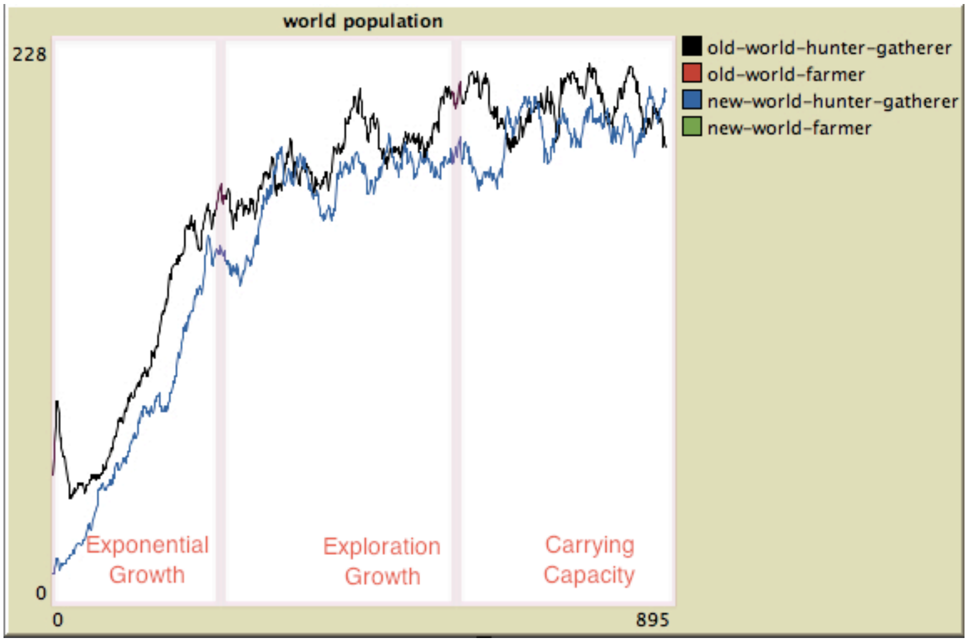

Figure 2: Hunter-Gatherer populations have three growth phases. First, during exponential growth, they spread quickly, extracting all easily available resources. Second, once the large, contiguous, habitable areas are occupied, new land is discovered by traversing mountain ranges, inhabiting islands, etc. Finally, they reach a carrying capacity, where population oscillations because of random births, deaths, and variable land yield.

from the perspective of individuals attempting to maximize their day to day rate of food returns, domestication is more likely an unintended consequence of intensified use of low ranked resources. In accordance with the prey choice model, another type of optimal foraging model, domestication tends to occur only after high ranked resources such as big game become sufficiently depleted so as to warrant inclusion of lower ranked species. This process of resources intensification prior to domestication is repeatedly observed around the world and is typically referred to as the broad spectrum revolution [11]. It is these lower ranked resources, especially weedy annuals, that tend to become the most critical initial domesticates in promoting the large, sedentary populations that ultimately burgeon into urban centers.

The domesticate origin loci provide our model with regions of potential domestication where agents who are unable to offset food shortages by movement begin intensifying their exploitation of caloric resources. This intensive interaction is simply modeled as a function of a given groups successive time spent occupying a given patch. Because species appropriate for domestication were not uniformly distributed on the globe, we have created "bread-basket" regions known to be historical origin of domestication, as listed above. Upon learning that the agent can no longer sustainably remain on their patch, and when no other viable patches exist to occupy, and, finally, if the patch exists within one of the identified bread-baskets, the agent will domesticate a species with some probability.

Once a species is domesticated, it can diffuse, or agents can carry it with them to other population or patches, respectively. However, it can only diffuse to patches with a similar bioproductivity value to that of the patch in which it originated. Continued use of the domesticate will result in increasing productivity. For the sake of simplicity, we indicate tribes that have discovered agriculture by changing their shape from a person to a leaf, as in Fig. 3. The size of the agent indicates its health and strength. The knowledge of domestication only passed down via reproduction. No exchange of knowledge occurs between "tribes." The environmental and behavioral patterns outlined above provide a theoretically grounded and empirically supported mechanism for the spread of populations around the globe. If Diamond's model is accurate–if geography indeed plays a role in the rate of spread and growth of human populations–then our model should show it. In particular, the rate of spread should be greater in the New World based on geographic topology alone as opposed to the timing of initial colonization.

As agents discover domestication, they put their efforts into agriculture instead of scouring the landscape for nourishment. Productivity and cooperation enhance crop yields and reduce caloric demands, increasing net-extractable calories. Eq. 1 is no longer an appropriate measure for famers, as sustained effort can improve the land, clear forests, and raise herds that can be shared by others. Therefore, we modify Eq. 1 to be

$$C_i \propto BP_i - \alpha \frac{BP_i^2}{\max_i BP_i} \frac{1}{f_i^2}, \qquad (2)$$

where f_i is the number of farmers[2] on patch i. This allows farmers to cooperate

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[2] If no farmers are on a patch ($f_i = 0$), Eq 2 is not used. Division by 0 is not a problem.

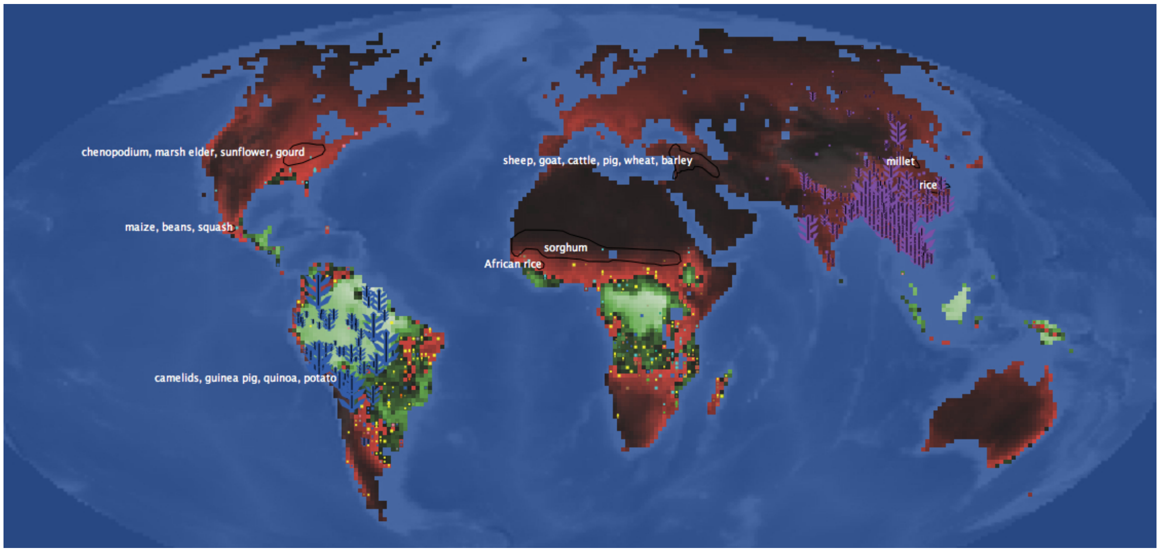

Figure 3: A screen capture from a run of our simulation. Hunter-gatherers are represented as people of different sizes, while agents who have achieved domestication are represented as plants. The color of the agent represents its tribe and is inherited. Beyond this, color has no significance. Domestication can only occur within outlined "bread-baskets," regions believed to be historical origins of the listed domesticated plants and animals, listed on page 4.

and exploit the land with much more efficiency, taking advantage of up to the full bioproductivity of the patch, as shown in Fig. 4. Regions that were previously unexploitable, such as deep jungle, become accessible to groups of farmers. When land is converted to farming, native flora and fauna are displaced. Hunter-gatherers who share patches with farmers lose productive land. Therefore, once a farmer arrives at a patch, any hunter-gatherers only extract 60% of net-exploitable calories, still given by Eq. 1. This drives hunter-gatherers away from farmers and into niche areas, or even to extinction.

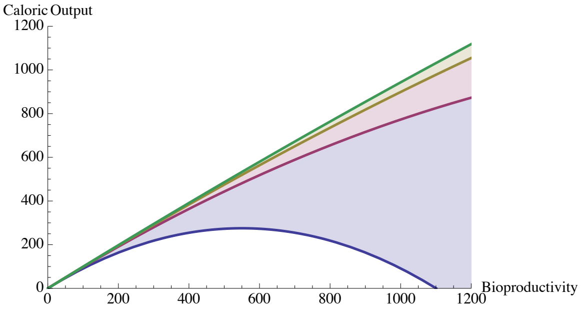

Figure 4: From Eq. 2, we see that farmers can cooperate to achieve higher yield from the land. The red curve shows the net-exploitable calories from two farmers, orange from three, and green from four. More farmers unlock the limit of full bioproductivity yield. Again, caloric output is in arbitrary units.

Once the emergence of farmers take hold, they quickly out compete hunter-gatherers, as can be seen in Fig. 5. Not only do they get a slight caloric advantage, but through cooperation, they have access to high yield areas inaccessible to hunter-gatherers. Not only do farmers out breed non-farmers, but they also strip away resources, leading to the demise of hunter-gatherers. Farmers take over via explosive growth, but this causes their population to overshoot the region's carry capacity. The subsequent population crash is only offset by the tribe of farmers discovering new territories, i.e. East Asian farmers migrating to Europe, then to Africa.

Our model over-favors farmers to the extent that the first tribe to discover agriculture frequently displaces all other tribes on their hemisphere, preventing a second origin. This does not mean our model has a fatal flaw, but it could be remedied by enforcing climate specific bounds to each crop, preventing Rice from gaining a foothold in Siberia or the Sahara. Tribes that rely on specific cultivars need to respect that cultivar's climatic restrictions. Second, we likely have a mismatch in timescales between movement, reproduction, and agricultural adoption, so individuals spread far more rapidly than historically observed once domestication been adopted. This can be adjusted by further parameter tuning and adding more information to agents beyond "farmer" or "not-farmer." For example, if we include Holdridge life zone information, we can add climatic data to bioproductivity, enriching the information on the patch's fundamental productivity. Also, by increasing the resolution on our map, we increase the patch distance between agents and increase the number of turns necessary for agents to find each other. This leads to geographic regions being more isolated, and a single tribe of farmers does not readily overwhelm the entire hemisphere. The trade-off is that the map supports more agents, slowing down the simulation. It also appears that the likelihood of adopting domesticates at a specific break-basket depends weakly on the resolution, because it alters the local distribution of suitable patches.

In the end, our simulation indicates that there certainly exist certain regions among the observed bread-baskets that are most likely to emerge as dominant world powers. First, there is East Asia, which spills over into Europe and Africa via what overlaps the spice road. Second, agriculture seems also to emerge in Africa, but rarely spreads beyond the Sahara. Central Africa provides such a rich basin of attraction that agents rarely need venture too far. Similarly, the Andes is the third frequent source of domestication. As in Africa, farmers densely South America, taking advantage of the high bioproductivity. Other areas, such as the Middle East, Central and North America, rarely emerge as sources of farmers in our simulations. Although this could be an artifact of our assumptions, each simulation tends to produce one emergence before that source dominates their respective hemisphere.

As we compare our results more carefully with the assumptions of Diamond, we see that agriculture does most frequently emerge in regions bordering lush, productive areas and arid regions. The population spill-over from these areas get pinned between a "population wall" on one side, and a dessert on the other, leading to the adoption of agriculture. Diamond pointed to the latitudinal climate bands of Eurasia as a central mode of trade and migration. We observe this as well, with agriculture in China quickly spreading to Europe and Africa, but agriculture in Africa has a much more difficult time emerging into Eurasia. In the end, simulation after simulation shows that chance is likely the single largest determinant of success. The super-exponential growth that takes place after domestication quickly overruns hunter-gatherer competition. Our simulation, in its initial form, seems to confirm Diamond's notion of geography as a key factor, but only further refinement will clarify if "history was wrong."

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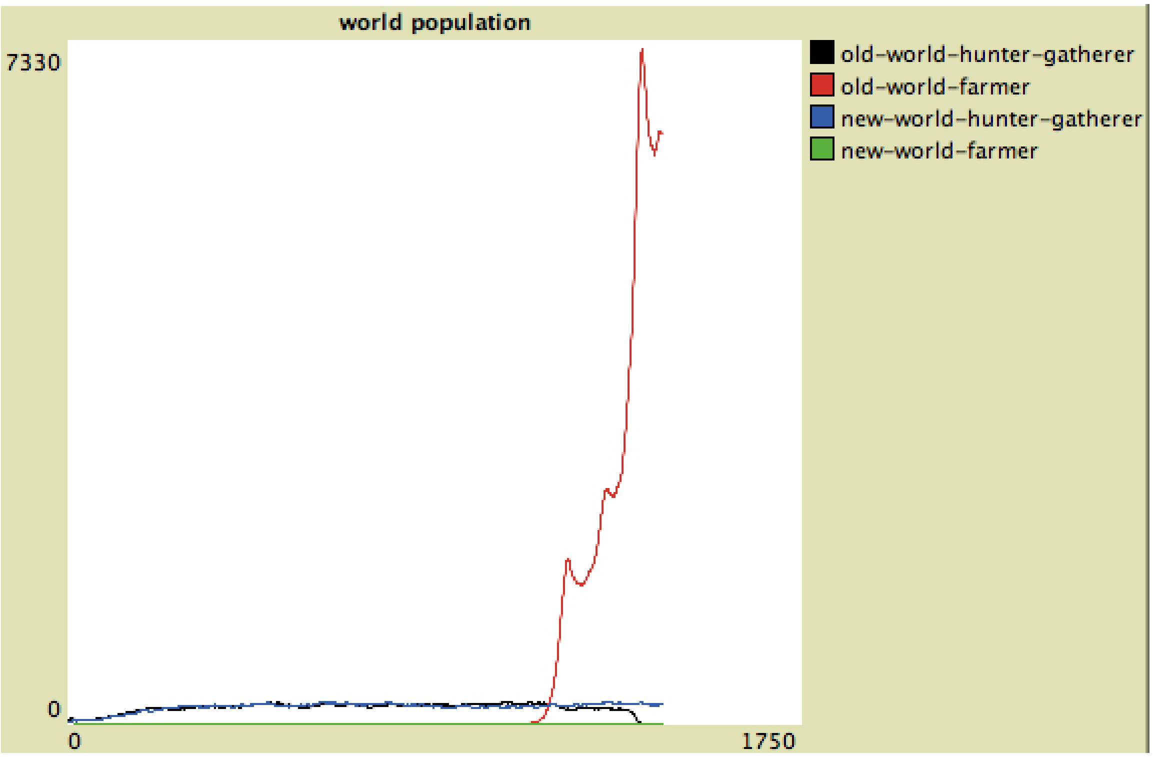

Figure 5: Typical emergence pattern for farmers originating in China. There is an initial super-exponential growth. Ultimately, cooperative effects reach a point of diminishing returns, and the population exceeds the carrying capacity of the local environment. Through exploration, such as discovering the Indian sub-continent and Europe, and, finally, Africa, the population goes through several boom-bust cycles. Once the African continent is overtaken by farmers, nearly all hunter-gatherers in the Old-World are out-competed. See Fig. 6.

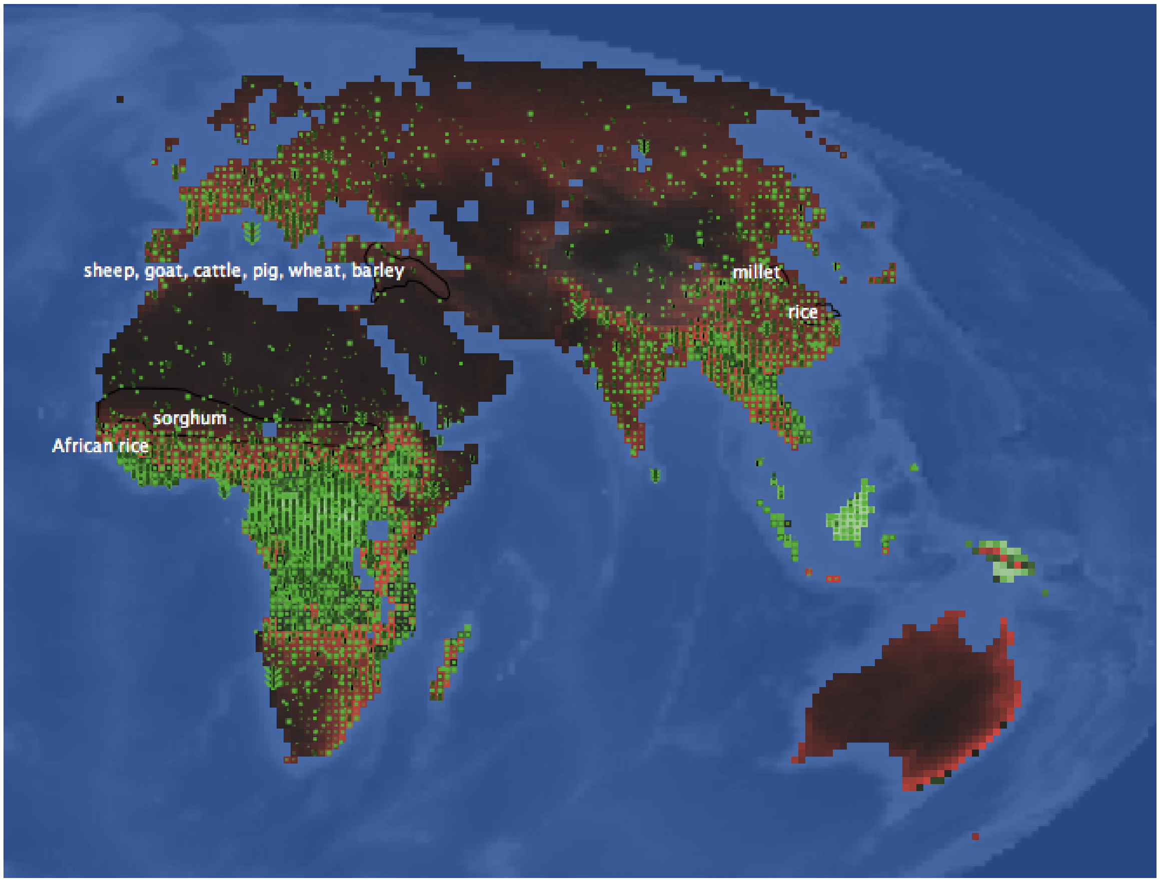

Figure 6: Resulting population distribution corresponding to growth curve in Fig. 5. Farmers first emerged in China. Second, they migrated to Europe, and, finally, they populated Africa, where the bulk of the hunter-gatherers resided. These hunter-gatherers were displaced, driving them to extinction, which can be seen in Fig. 5.

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