

# Agents Adopting Agriculture: Modeling the Agricultural Transition

Elske van der Vaart, Bart de Boer, Albert Hankel, Bart Verheij

Artificial Intelligence, Rijksuniversiteit Groningen, Grote Kruisstraat 2/1  
9712 TS Groningen, the Netherlands  
elskev@ai.rug.nl

**Abstract.** The question “What drove foragers to farm?” has drawn answers from many different disciplines, often in the form of verbal models. Here, we take one such model, that of the ideal free distribution, and implement it as an agent-based computer simulation. Populations distribute themselves according to the marginal quality of different habitats, predicting settlement patterns and subsistence methods over both time and space. Our experiments and our analyses thereof show that central conclusions of the ideal free distribution model are reproduced by our agent-based simulation, while at the same time offering new insights into the theory’s underlying assumptions. Generally, we demonstrate how agent-based models can make use of empirical data to reconstruct realistic environmental and cultural contexts, enabling concrete tests of the explanatory power of anthropological models put forward to explain historical developments, such as agricultural transitions, in specific times and places.

## 1 Introduction

To us modern agriculturalists, “Why farm?” seems like a non-question. Intensive food production is what supports our large, complex societies. It frees many of us to become specialists, enriching life in ways beyond mere provisioning: as doctors, entertainers, scientists. Without crop cultivation, our current population densities and growth rates would be impossible to sustain.

From that perspective, the advantages of agriculture over hunting-gathering, our earlier subsistence method, appear obvious. The daily toil of foraging for wild foods can only result in an existence best characterized as “nasty, brutish and short”, as Thomas Hobbes once put it. Our ancestors’ eventual switch from foraging to farming can then be explained simply by people discovering how to accomplish it.

The problem with this reasoning is that it rests on false assumptions. Our food crops today have characteristics carefully selected for by humans. On the whole, they are annuals, easy to sow and easy to harvest. The first farmers had much less to work with. If we take maize as an example, its likely precursor, *teosinte*, a wild cereal, produces a harvest only every other year, with tiny, brittle cobs and seeds nearly impossible to extract from their rock-hard casings [8].

In fact, it has become increasingly clear that the first agriculturalists probably worked harder [3], enjoyed less diverse diets [8] and experienced more disease [1]

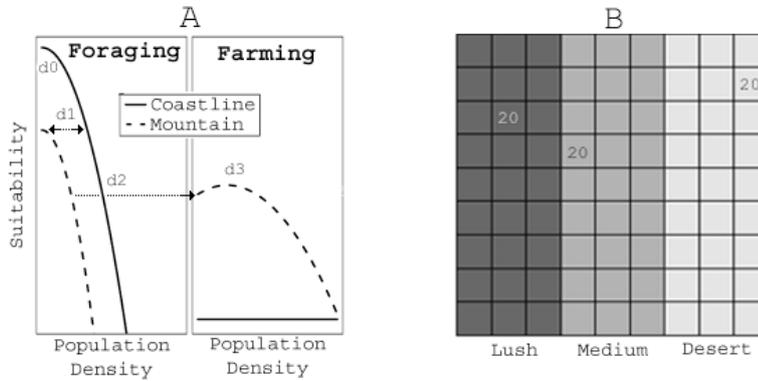
than their immediate hunter-gatherer predecessors. So what drove those first farmers, ten thousand years ago in the Fertile Crescent [5], to take to cultivating crops and raising livestock, considering the hardships it imposed? Why there? Why then? And what about the other independent centers of agriculture, like the Andes, or the Far East [5]? Were the causes the same, or different?

Kennett and Winterhalder [10] present a collection of papers on behavioral ecology approaches to these questions. In this context, behavioral ecologists consider the ecological and evolutionary roots of subsistence change and how it helps individuals adapt to their environments. The mathematical and graphical theories of behavioral ecology are meant to capture the decisions and tradeoffs of individuals, and yet often include none, as they model only population-level behavior. As such, Winterhalder and Kennett [14, page 19] conclude, "...although there are at present no agent-based models of domestication or agricultural origins, behavioral ecology adaptations of the agent-based approach appear an especially promising avenue for research".

This paper is the result of a first attempt to realize that promise. To this effect, we have taken one of the models from [14] and implemented it as an agent-based computer simulation. Our research questions were simple. If we follow the principles of the model in question, will our agents behave like the theory predicts? And if so, what can the simulation teach us about its underlying assumptions? The model we selected for this treatment, that of the *ideal free distribution*, is a theory of habitat choice. It assumes that any area can be divided into a number of discrete habitats, differentiated by their *suitability*, and that populations will distribute themselves according to the *marginal quality* of those habitats [14].

Figure 1A provided an illustration of use of suitability curves in the ideal free distribution. Imagine human colonists, arriving on a pristine island, consisting of two habitats: the coastline and a mountain. The mountain is covered with dense forests; the coastline is sunny and rife with fish. If the assumptions of the ideal free distribution hold, all colonists will initially settle on the coast, because of its greater 'suitability' for human residence ( $d_0$ ; numbers in brackets refer to specific densities in Figure 1A). As population pressure rises, the coastal habitat becomes less and less attractive due to crowding and resource depletion, reducing its 'marginal quality'. Eventually, the mountain's suitability will rival that of the coast ( $d_1$ ). From this density onwards, people should start settling in the mountains, with further population growth spread equally over both habitats [inspired by 11, 12].

Let us further hypothesize that our island is home to a small stand of wild cereals, initially ignored by the colonists in favor of other, more easily procured food sources. As population grows, however, and these other food sources are exploited to carrying capacity, suitability of both habitats for human *foragers* drops considerably. At some point, artificially increasing the amount of wild cereal by planting and tending it may become worthwhile. At this density ( $d_2$ ), any additional residents should take to the mountains, where this type of food production is possible. In fact, these first farmers might actually *increase* the suitability of that habitat for other agriculturalists by clearing large sections of the forest, which should result in more people switching, until some maximum optimal density is reached ( $d_3$ ) [11, 12].



**Fig. 1.** A: Suitability of example habitats relative to population density and subsistence method, numbered densities refer to descriptions in text [after 11, 12] B: Simplified 9x9 model scape, 3 bands of 20 agents shown

Essentially, by comparing the ‘suitability curves’ (see Figure 1A) of different habitats with respect to changes in population density, the ideal free distribution model can make predictions about human settlement patterns over both time and space. By adding suitability curves for farming, the model can also predict people’s subsistence strategies, as well as where they will adopt them and when they will switch [11, 12].

Using archeological evidence to construct appropriate suitability curves, the ideal free distribution theory has recently been applied to questions of agricultural origins in Eastern Spain [11] and Oceania [12]. In theory, realistic agent-based simulations, designed to mimic actual environmental and cultural conditions, offer possibilities for testing the explanatory power of such verbal models.

In this paper, we report on a first step in that direction. We have built a simple three habitat system and populated it with digital foragers and farmers, incorporating as much empirical data as possible. Our two goals are to show that 1) this simulation is capable of reproducing the predictions of the ideal free distribution model and 2) that it can at the same time provide insights into the validity and applicability of its underlying assumptions.

Our simulation, loosely based on Epstein and Axtell’s sugarscape model [6], consists of a square grid of patches, divided into three discrete habitats. Each patch is inhabited by both *prey* and *cereal*, simulated by reasonably realistic growth rates, population sizes and energy values. The three habitats are 7x21 patches each, and differ only in the maximum densities of prey and cereal that can be supported by each patch. A reduced version of this model is Figure 1B.

Every time step, representing a year, the agents that inhabit these habitats must obtain enough food to survive, which they can accomplish by hunting prey, gathering cereal, or starting farms. Every subsequent time step, prey and cereal grow back, and the agents select new patches, preferring the most suitable ones. Reproduction grows the agent population until prey and cereal become seriously depleted, prompting adaptation in the form of habitat migration or subsistence change.

## 2 The Simulation Model

Considering that our explicit aim is to generate insight into an anthropological theory, it is of prime importance to ensure that any results will make sense to anthropologists. To this end, we have attempted to keep our model as realistic as possible, given the constraints of the data available to us. Our agent-based examination of the ideal free distribution involves a *scape* consisting of *habitats*, *food resources* to populate those habitats, *agents* that utilize these food resources and a set of *behavioral rules* that specify agents' subsistence behavior.

To capture the essential aspects of the ideal free distribution theory, the quality of our habitats must change with population density, and the agents must be able to make informed choices about which habitat is currently most suitable. Winterhalder *et al.*'s [13] mathematical model of optimal foraging theory, which considers 'the interaction of human population, diet selection, and resource depletion', provides a realistic quantification of both these aspects.

In this model [13], different food sources become increasingly hard to obtain as they become scarcer, increasing *search times*, which naturally occurs as population pressure rises. This reduces foraging efficiency and thus negatively impacts habitat suitability, which is measured as *net acquisition rates* [11]. In [13], the model is applied to questions of diet choice in a fixed area; in our simulation, we expand it to answer questions of habitat choice in a larger region, by explicitly including the dimension of space.

### 2.1 Characteristics & Properties of the Habitats, Food Resources & Agents

*Scape & Habitats.* To simulate hunter-gatherer behavior, one must first simulate a world of food to hunt and gather. Our world consists of 21x21 patches, each representing 300 square kilometers, with time steps (*epochs*) corresponding to a year. The edges of the world are true edges. According to [3] most foraging groups build base camps, which they may move once or twice a year. A forager can cover about ten kilometers and still return to such a base camp the same day; using this as a radius, we can calculate a home range of approximately 300 square kilometers [13]. This is what determines our patch size. Our three habitats are 7x21 patches each, colloquially termed the '*lush*', '*medium*' and '*desert*' habitats, ordered from left to right in the scape and differentiated only by their carrying capacities for different food resources (see Figure 1B).

*Food Resources.* Our hunter-gatherers have two dietary options, *prey* and *cereal*, which populate each patch. The prey has characteristics inspired by large ungulates; the cereal is loosely based on wild barley. Here, energy value ( $e_i$ ) is the calories provided by a single prey or kilo of cereal; *handle time* ( $h_i$ ) is the total time required to catch, clean and cook a prey once spotted, or harvest, thresh and prepare a kilo of cereal gathered once located; *carrying capacity* ( $C_i$ ) is the maximum prey or cereal population that can be supported by a square kilometer of patch and growth rate ( $r_i$ ) specifies the intrinsic rate of increase of each, where the index  $i$  specifies prey  $p$  or cereal  $c$ . The prey values were calculated from anthropological data in [13]; the cereal

characteristics represent ballpark figures, chosen as conscientiously as possible using data from [7, 8, 9].

**Table 1.** Characteristics of Prey & Cereal

Type	Energy value ( $e_i$ ) (Cals)	Handle time ( $h_i$ ) (minutes)	Carrying capacity ( $C_i$ ) (no or kilos/km <sup>2</sup> )			Growth rate ( $r_i$ ) (no or kilos/year)
			Lush	Medium	Desert	
Prey (p)	13800	235	8.0	5.4	2.6	0.7
Cereal (c)	3390	120	600	400	200	1

Both prey and cereal grow according to equation (1), taken from [13] were  $p_i(t)$  is the population size of food type  $i$  at time step  $t$ ,  $C_i$  is the maximum carrying capacity for food type  $i$  and  $r_i$  is its intrinsic rate of increase. The equation is applied per patch. This results in cereal and prey slowly growing towards their carrying capacities, then stabilizing. In principle, there is no influence of cereal and prey densities between patches, unless either cereal or prey completely disappears from a patch. In that case, each of its eight neighboring patches that *does* still have a viable population of the resource in question has a 10% chance of repopulating the depleted patch each year. A ‘viable population’ is either 100 prey or 400 kilos of cereal; these are also the initial population sizes of each for a repopulated patch.

$$p_i(t+1) = p_i(t) \frac{C_i e^{r_i}}{C_i(1 - s_i t(1 - e^{r_i}))} \quad (1)$$

*Agents.* The agents in our simulation represent small bands of hunter-gatherers. Every band starts as a group of 20 people. Every times tep, each of those 20 people has an 0.02 chance of reproducing, which is supposedly roughly characteristic of actual hunter-gatherers [13]. Once a band is made up of 40 individuals, it splits in two, each again representing 20 people. Every time step, the bands must forage 2000 kilocalories (Cal) for each of their group members, for each day of the year. Maximum foraging time is fixed at 14 hours per day. If there is shortfall, group size is scaled down to the number of people adequately fed. Foraging, however, also has costs; 4 Cal per minute ( $c_s$ ) spent searching for prey or cereal, and 6 Cal per minute ( $c_h$ ) spent catching or harvesting them [13].

**Table 2.** Agent Characteristics

Characteristic	Value	Characteristic	Value
Group size	20 – 40 (people)	Search cost ( $c_s$ )	4 (Cals/min)
Min. energy	2000 (Cals)	Catch cost ( $c_c$ )	6 (Cals/min)
Max. forage time	14 (hours)	Search speed ( $s_s$ )	0.5 (km/hour)
Growth rate	0.02 (per year)	Search radius ( $s_r$ )	0.0175 (km)

*Search Times.* The catch times of prey and cereal are fixed; the search times for each depend on population density [13] within a patch. The rarer a food source has become, the longer it takes to locate. It is also dependent on the speed at which agents search ( $s_s$ ), and their search radius ( $s_r$ ) as they do so (i.e. ‘How far can they see?’) (see

Table 2). Search times are then calculated using equation (2), where  $s_i$  is the search time for food type  $i$  and  $d_i$  its current population density.

$$s_i = \frac{1}{s_s \cdot s_r \cdot 2 \cdot d_i} \text{ (in minutes/prey)}. \quad (2)$$

*Net Acquisition Rates.* Now that we have specified the time it takes to catch ( $h_i$ ) and find ( $s_i$ ) each type of food source, their respective energy values ( $v_p$  and  $v_c$ ) and the energy costs incurred in obtaining them ( $c_h$  and  $c_s$ ), we can calculate the ‘net acquisition rates’ (NAR) for each; that is, how much energy an agent gains for each hour spent hunting for prey or gathering cereal. The higher the net acquisition rate, the more efficient foraging for that food type is. The net acquisition rate of food source  $i$  at time  $t$  is then equal to the values in Table 3, as calculated per habitat.

**Table 3.** Net Acquisition Rates

	<i>NAR ‘Lush’ Habitat</i> (Cals/hour)	<i>NAR ‘Medium’ Habitat (Cals/hour)</i>	<i>NAR ‘Desert’ Habitat</i> (Cals/hour)
Prey (p)	965	674	281
Cereal (c)	1298	1256	792
Farming (f)	677	605	481

$$NAR_i = \frac{e_i}{s_i + h_i} - \frac{s_i}{s_i + h_i} c_s - \frac{h_i}{s_i + h_i} c_h. \quad (3)$$

## 2.2 Behavioral Rules

Our agents now have properties, a scape of habitats to move about in, and two types of food resources to forage for. In this section, we define the rules that guide their behavior. The ideal free distribution is a model of habitat choice, which assumes that individuals populate habitats according to their marginal quality. Our agents thus need to have a sense of what makes a patch *suitable*, which depends on their *dietary preferences*. Also relevant is the *range* in which agents can evaluate patches, and what the costs and benefits are of *food production*.

*Suitability & Dietary Preferences.* A patch’s suitability may be measured by ‘the production of young or rate of food intake’ [14] of the initial occupant. Our agents rank patches by prey density first, cereal density second, reflecting the large percentage of meat found in most foragers’ diets [4], and the greater prestige associated with hunting over gathering as it is observed in most hunter-gatherer cultures. Once a patch has been selected, agents hunt prey and gather cereal in proportion to their net acquisition rates; as prey becomes scarcer relative to cereal, it is consumed less (see equation (4)). Consumption of a food source stops if its net acquisition rate drops below zero.

$$\text{percentage of food source } i \text{ in diet} = \frac{NAR_i}{\sum_{\text{All food sources } j} NAR_j} \quad (4)$$

*Range.* Every time step, each band starts in one patch, and may choose to move to another, which is always the most suitable patch it has knowledge of. This represents a small group of hunter-gatherers moving its base camp once a year. But which patches are considered to be ‘in range’? Realistically, one might assume that these hunter-gatherers only have some sense of the area just outside their home range, and hence can only evaluate their own patch and the eight surrounding ones.

However, one of the ideal free distribution’s explicit assumptions is that ‘...all individuals have the information to select and the ability to settle in the most suitable habitat available.’ [12]. This would be best modeled by each agent having perfect knowledge of the suitability of each other patch in the scape. In our experiments, we try both options. Costs of moving are not considered, as ideal free distribution model assumes that those costs are ‘...negligible, when compared to the benefits of optimizing long-term habitat choice.’ [10].

*Food Production.* Given that our simulation is intended to provide insights into behavioral ecology approaches to agricultural transitions, we must model some form of food production. Using [7, 8] as sources, some educated guesswork allows us to derive the additional kilos a square hectare of cultivated cereal might yield ( $c_k^+$ , where  $c_k$  is the wild harvest), as well as the time it takes to produce a kilo of cereal by farming ( $t_f$ ) (equations (5)&(6)), where  $A$  is the number of hectares of cereal that can be tended by working an hour daily. This is *excluding* harvest time, which is considered to be identical to that of wild cereal, as given by Table 1.

$$c_k^+ = 0.25(1000 - c_k) \quad (\text{in kilos/hectare}) . \quad (5)$$

$$t_f = \frac{1}{h \cdot (c_k + c_k^+) \cdot 365} \quad (\text{in hours/kilo}) . \quad (6)$$

If we assume that it takes approximately half an hour a day to tend a hectare of cereal, and that both tending and harvesting cereal are strenuous activities [8], costing 6 Cals of energy/minute ( $c_h$ ), we can then derive net acquisition rates for farming cereal in the three different habitats, as demonstrated by table 3. This means that the efficiency of farming is *independent* of population density. The area which is suitable for agriculture is bounded, however, at 10% of each patch [7]. Food production is only practiced if its net acquisition rate becomes higher than that of foraging for cereal; it then enters the diet in accordance with equation (4). Agents can thus forage exclusively, farm exclusively, or practice some mixture of both.

### 3 Experiments & Results

Our first goal is to ascertain to what degree our simulation reproduces the predictions of the ideal free distribution. To this end, we run the model in three different configurations. First, as a single food source environment, where agents can only forage for

cereal (Experiment I). Second, as a hunter-gatherer society, where both cereal and prey are available, but switching to food production is impossible (Experiment II).

Third, as the full simulation, where agents can forage or farm as desired (Experiment IIIa). In these three experiments, agents have access to the suitability of every patch in the scape, to mimic the ideal free distribution model’s assumption of ‘perfect information’ [12]. As a test of the consequences of this assumption, we will also run the full simulation with bands that can only evaluate the suitability of their own patch and its eight neighboring patches (Experiment IIIb).

In each of these experiments, we initialize the model by seeding five bands at random locations throughout the scape. Bands are awarded the opportunity to select patches in fixed order, with older bands first and younger bands last. This represents the process of ‘daughter populations’ splitting off and seeking new habitats. Unless otherwise stated, an experiment consists of 10 runs of 3000 epochs each.

### 3.1 Experiment I: Gathering

*Setup & Predictions.* In this first experiment, agents must make their livelihoods exclusively by gathering, which means they rank patches by cereal density only. Our agents have perfect information and free access to every patch on the scape; the ideal free distribution model straightforwardly predicts that they should colonize the ‘lush’ region first, followed by the ‘medium’ area and tailed by the ‘desert’ habitat, at a speed that maximizes rate of food intake throughout the scape.

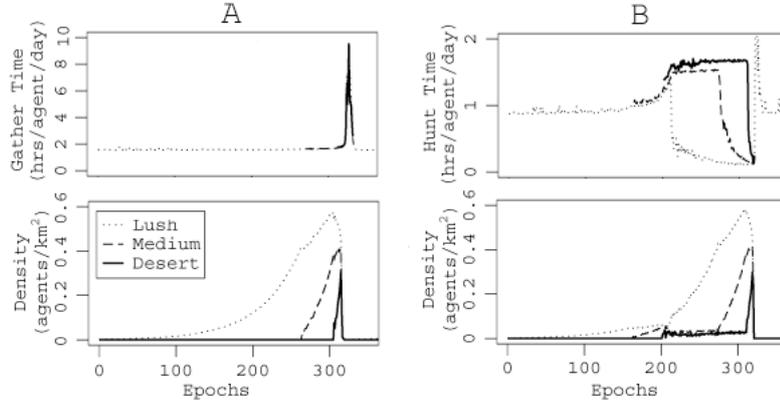
*Results.* All bands are immediately drawn to the ‘lush’ area, where population grows until about epoch 270 ( $\mu = 267$ ,  $\sigma = 5$ ), when the first bands migrate to the ‘medium area’. Expansion into the ‘desert area’ follows around epoch 310 ( $\mu = 310$ ,  $\sigma = 5$ ), with population still growing, reaching a maximum of approximately 0.39 ( $\mu = 0.39$ ,  $\sigma \approx 0$ ) agents/km<sup>2</sup>. Finally, around epoch 330 ( $\mu = 326$ ,  $\sigma = 8$ ), carrying capacity of all three habitats is simultaneously exhausted, resulting in a massive population crash. The survivors pull back towards the ‘lush’ area, and the process restarts, with cycles of approximately 270 epochs ( $\mu = 267$ ,  $\sigma = 31$ ). Comparing average gather times between habitats reveals no significant differences in any of the runs (two-tailed t-test,  $p > 0.05$  for all pairs of average gather times). Figure 2A shows one run’s first cycle of agent densities and gather times over all three habitats.

*Discussion.* The agents are as ideally free distributed as possible. All agents, all over the scape, work nearly equally hard during each time step, having distributed themselves unevenly over the habitats to do so.

### 3.2 Experiment II: Hunting & Gathering

*Setup & Predictions.* Now, agents have both prey to hunt and cereal to gather, which agents do relative to both food sources’ net acquisition rates (equation (4)). In essence, this means they have a preference for a mixed diet, but are willing to be flexible as resource densities change. Patches are selected by prey density first, cereal density second. The order in which habitats are settled is easily predicted as ‘lush’,

then ‘medium’, then ‘desert’, but what an “ideal” distribution is in this situation, is



**Fig. 2.** A: Top, average time spent gathering in the first cycle of a sample run of Experiment I; note how the lines for the different habitats actually cover each other; Bottom, average agent densities of the same run and cycle. B: Top, average time spent hunting in the first cycle of a sample run of Experiment II; Bottom, average agent densities of same cycle and run

unclear.

*Results.* All agents immediately relocate to the ‘lush habitat’, expanding into the ‘medium’ habitat around epoch 160 ( $\mu = 162$ ,  $\sigma = 5$ ) and the ‘desert’ habitat about 40 epochs later ( $\mu = 200$ ,  $\sigma = 6$ ), with population steadily increasing until approximately epoch 300 ( $\mu = 310$ ,  $\sigma = 40$ ), when carrying capacity is once again simultaneously exhausted all over the scape, causing massive drops in agent totals. As an example, the first cycle of one run is shown in the bottom panel of figure 2B.

The first migration to the second and third habitats is the result of agents following prey; the quick population increase in the ‘lush’ habitat after epoch 200 is the result of prey having become so depleted that many agents are having to live without meat; with no reason to follow prey to the lesser habitats, they crowd the ‘lush area’ until its cereal is so depleted that it becomes worthwhile to gather in the ‘medium’ and ‘desert’ regions as well. Figure 1B shows an example, but a similar process occurs in all cycles and runs.

Average foraging times, however, vary significantly between habitats. If we compare the time spans where all three regions were populated, agents in the ‘lush area’ worked an average of almost two hours ( $\mu = 1.88$ ,  $\sigma \approx 0$ ) per day, agents in the ‘medium’ area foraged for over two and half hours ( $\mu = 2.67$ ,  $\sigma \approx 0$ ) while agents in the ‘desert’ area spent almost three-and-a-quarter hours foraging daily ( $\mu = 3.21$ ,  $\sigma \approx 0$ ).

*Discussion.* Judged by the differences in the agents’ average workloads, the obtained distribution can hardly be considered ideal for ‘rate of food intake’. On closer inspection, however, it appears that the distribution may be slightly fairer than it appears. The reason the agents in the ‘lush’ area forage so little, is that there is no prey left to catch. If we consider the average energy from hunting in epochs where all three habitats are occupied, agents in the ‘lush’ area eat the least meat ( $\mu = 49$  Cals,  $\sigma = 1$ ) and agents in the ‘medium’ area the most ( $\mu = 93$  Cals,  $\sigma = 1$ ), while agents in the ‘desert’ area are in the middle ( $\mu = 81$  Cals,  $\sigma = 1$ ).

### 3.3 Experiment III: Hunting, Gathering & Farming

*Setup & Predictions.* Agents can now hunt, gather or farm, with gathering initially twice as efficient as farming. Agents still prefer the mixed diets of Experiment II, with food production only considered in case its net acquisition rate outranks that of gathering cereal. Initially, agents should distribute themselves over the three habitats as they do in Experiment II, but rather than population crashing, agents should switch to farming when prey and cereal first run out, starting in the ‘lush’ region, then the ‘medium area’, then the ‘desert’ habitat.

This system is essentially deterministic, as it is independent of initial conditions and involves so many agents that random fluctuations cancel each other out (Pearson’s correlation coefficient of agent totals per epoch: 0.99 per any two runs). As such, it seems safe to report on only one run per configuration. We run this model both with perfect (IIIa) and local information (IIIb).

*Results, IIIa.* In the perfect information condition, agents first settle in the ‘lush’ habitat, colonizing the ‘medium’ habitat in epoch 143 and the ‘desert’ habitat in epoch 181. Food production starts in epoch 215, in the ‘lush’ area, where the number of farm hectares steadily climbs until epoch 459, when every single patch of ‘lush’ arable land is in use, prompting new farmers to migrate towards the ‘medium’ habitat, and later to the ‘desert’ habitat (epoch 492).

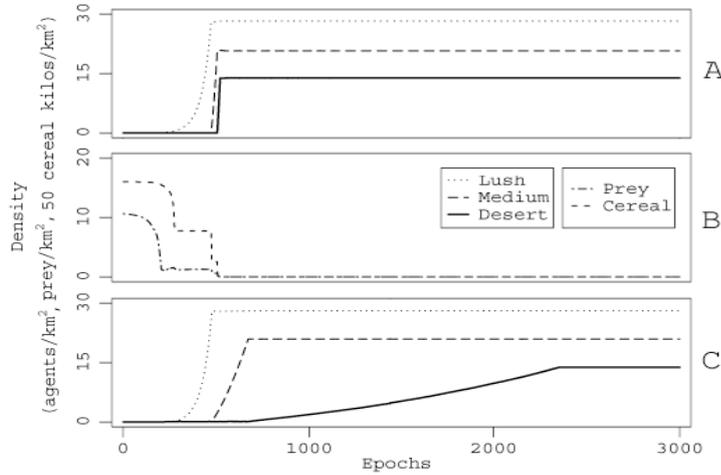
By epoch 507, all possibilities for agriculture have been seized, and agent densities stabilize at an average of 20 agents per square kilometer (Figure 3A). In the meantime, both wild cereal (epoch 499) and prey (epoch 508) have become extinct (see Figure 3B). Results of the ‘local information’ (IIIb) configuration runs are qualitatively similar, with the glaring exception of the timing. It takes up to epoch 2685 for the ‘desert’ habitat to fully fill up with farmers (Figure 3C).

*Discussion.* The extinction of prey and wild cereal is the result of equation (4), which allows farmers to continue “hunting and gathering on the side” once food production enters the diet. The large time difference in completion of the agricultural transition between the ‘perfect information’ and ‘local information’ condition is caused by lack of distribution possibilities. The high population densities of the farmed habitats cause large numbers of new bands to be formed, but they have nowhere to go if they cannot see the relatively unpopulated ‘desert’ area.

## 4 Conclusions

The question of why our ancestors first switched from foraging to farming has fascinated scientists for decades. In this paper, we hoped to offer only the suggestion of a new method, not a new model, to the study of this fascinating issue. We took up Winterhalder & Kennett’s [14] suggestion to implement a behavioral ecology model as an agent-based simulation, consisting of three discrete habitats, and evaluated if our simulation could reproduce the model’s predictions. We have shown that:

In the simplest possible implementation of the model, with only one food source and complete information, an ideal free distribution of the agents does indeed emerge.



**Fig. 3.** A: Agent population densities of Experiment IIIa, foragers & farmers with perfect information; B: Prey and cereal densities of Experiment IIIa; C: Agent population densities of Experiment IIIb, foragers & farmers with local information

Agents in all three habitats spend an equal amount of time gathering food. Hence, under these conditions, the ideal free distribution model is retained.

If there are two food sources: highly desirable but hard to catch prey and less desirable, but easy to collect cereal, agents in different habitats end up spending different amounts of time. At first sight this contradicts the ideal free distribution model. However, agents that spend more time have more meat in their diets. It thus seems that the distribution remains ideal if a more complete definition of ‘ideal’ is used.

Agriculture can and does emerge in our simulations, and it emerges in the way that is predicted by the ideal free distribution. Furthermore, wild prey and cereal go extinct, meaning that agents cannot go back to their original hunting-gathering life style. This conforms to the ratchet effect that is observed in human populations. When the assumption of global information is lifted, populations no longer distribute themselves ideally. This causes the transition to agriculture to take longer.

It seems that, generally, our simulation has fulfilled our two initial goals. We have reproduced the predictions of the ideal free distribution theory in two settings – a single prey system and the transition to agriculture, assuming perfect information – and generated insight into its underlying assumptions in two others. Namely, the paucity of ‘rate of food intake’ as a general measure of habitat suitability, and the fact that assuming global information rather changes the model’s predictions, at least in our simulation. For the future, we think that agent-based simulation can do more than just confirm predictions and point out potential shortcomings in existing theories – they can actually help solve them.

Realistically representing a preference for meat is practically impossible in a verbal model, but easy to implement in an agent-based simulation. The same goes for specifying the amount of information available about other habitats. Anthropological findings may often offer some idea about what is plausible in any given historical or environmental setting, but quantifying the effects of these local variables in a verbal model is difficult, and usually very hard to verify empirically. Agent-based models

offer an easy way of simulating specific conditions and cultural practices (for a recent example, see [2]), and thus seem to offer much explanatory power when it comes to considering agricultural transitions in specific times and places.

## Acknowledgements

We would like to thank Gert Kootstra for his valuable input in the early phases of this project, and Tim Dorscheidt for many spirited discussions.

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