Fire from the seas: modeling the use of seaweed as fuel by the ancient Atacama Desert's hunter-fisher-gatherers

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Abstract

I. INTRODUCTION

A. Introduction: past human-plant interactions and the archaeobotany of coastal hunter-fisher-gatherers

Within the social sciences, there has been considerable debate surrounding the conceptualization of hunter-gatherers; diverse interpretations of hunter-gatherer classification underscore distinct facets, encompassing elements such as social organization, mobility, and subsistence strategies (Barnard 1983; Bettinger 1987; Lee 1992; Pluciennik 2020). In archaeology, there has also been a debate about the existence of a distinct hunter-gatherer archaeology, with scholars distinguishing between different approaches that focus primarily on specific types of archaeological material remains or particular research questions (Warren 2021). Following this line of thought, this paper aims to contribute to hunter-gatherer archaeobotany, which has already been recognized in the literature (Mason and Hather 2016).

Hunter gatherer archaeobotany seeks to analyze plant remains within archaeological foraging economies contexts, revealing insights into past human-plant interactions and the ecological dynamics that shaped these subsistence practices (Ugalde and Kuhn 2024, Weiss et al. 2004, Wollstonecroft 2011, Coughlan et al. 2018). Although staple identification and management have been extensively studied in depth in agricultural contexts, the role of wild plant resources and fuel management is equally crucial to understanding hunter-gatherer economies.

The identification of fireplaces, in particular, plays a significant role in ancient contexts (Scott and Hosfield 2021), in which such archaeological features allow distinguishing anthropic from non-anthropic deposits. In addition, the possibility of using charred remains for radiocarbon dating makes fireplaces and hearths a central research topic within the archaeology of hunter-gatherers (McCauley et al. 2020, Ptáková et al. 2021, Sobkowiak-Tabaka and Diachenko 2021 Salise-Sugiyama 2024). Furthermore, the analysis of charred remains can reveal insights into seasonal patterns of habitation and resource utilization, shedding light on the adaptive strategies employed by these communities in response to ecological changes, resource changing availability or resource depletion. Consequently, anthracology and, more specifically, the identification of resources used as fuel play a central role in hunter-gatherer archaeobotany (Caruso Fermé 2019; Mas et al. 2021; Théry-Parisot 2010).

Despite the fact that raw materials other than wood as fuel have been identified in several hunter-gatherer sites (see a review by McCauley et al. 2020), plant resources (mainly hardwood and softwood) constitute the main source of fuel in most ecological settings. Therefore, wood availability might have conditioned hunter-gatherer livelihoods in the same way as food resources or the availability of raw materials. In specific settings, such as arid areas, where plant biomass is scarce, patterns fuel use are constrained by the availability of plant resources. Nowadays, deserts and arid landscapes constitute about 17 per cent of Earth's land-mass. These landscapes have been home to diverse socioecological systems that developed different types of adaptations to thrive in such harsh conditions. Despite this, the biodiversity richness in arid areas remains partially unknown, as many species are hidden in desert seed banks. For this reason, proper recording requires the use of more than one method, as well as observations carried out over several years (Carrasco-Puga et al. 2021).

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Coastal hunter-gatherer communities exhibit a variety of distinctive traits and follow particular developmental trajectories, positioning them as valuable and differentiated subjects of archaeological investigation (Zurro et al., 2009; Ahedo et al., 2019; Franch et al. 2024). Coastal deserts are areas where human communities have adapted to changing shorelines, scarcity of fresh water and land resources In contrast, coastal deserts might border extraordinarily rich marine ecosystems, allowing for the development of unique "maritime traditions". Understanding these adaptations not only sheds light on human resilience in extreme environments, but also informs current conservation efforts initiatives in analogous environments.

The archaeobotany of arid and coastal areas raises additional challenges that require new approaches and innovative methodologies, allowing to go beyond plant remains identification and past environments reconstruction. Complementarity between land and sea resources is a standard for coastal communities, adding complexity to an archaeobotany of coastal hunter-fisher-gatherers. Such resource complementarity necessitates the development of a marine archaeobotanical approach that ex-

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plicitly includes algae and seagrasses as components of the plant-based resources exploited by past communities (REF).

The present study brings together the issues discussed above, proposing marine archaeobotany as a key component of a coastal hunter-gatherer-fisher archaeology, through a paradigmatic case study: the hunter-gatherer archaeology of the Atacama coast. Within this framework, we propose a model of seaweed use as fuel—archaeologically evidenced in the region—with the aim of understanding the practice of marine fuel use through the lens of human ecology and resource management.

B. Atacama past hunter-gatherers as a case study for the understanding of plant-human relationships in arid coasts

The Atacama Desert has witnessed human occupations for the last 10.000 years (Latorre et al. 2013) despite being the most arid region on the globe after the Arctic. The coastal Atacama Desert spreads between the Pacific and the Cordillera Costanera for 180,000 km2, with widths up to 100 km. In the Atacama, water sources are extremely scarce. Plants tend to appear distributed in narrow bands or at the top of hills where coastal fogs allow for plant growth (Arroyo et al. 1988, Díaz et al. 2012).

The concentration of archaeological sites supports the hypothesis of a growing population between 11 and 4 cal kyr BP (REF). This demographic increase is commonly linked in the specialized literature to the intensification of marine-oriented technologies (REF), suggesting the availability of sufficient freshwater, fuel, and a diversified food supply that would have supported sustained population growth. While this must be true, and even considering that in some areas vegetation in the past was more abundant than in the present (an example would be the PdT - Pampa del Tamarugal, a palaeowetland that covered more than 600 km2 in the Atacama desert, see Acosta and Rivera 2022), availability of fuel might have been a challenge for sustaining population needs.

Whenever available, wood is often prioritized, although different types of fuel (such as dung, bones, or peat) have been documented in both ethnographic and archaeological contexts (Aldeias 2017). When referring to coastal areas, seaweeds have also been documented as an alternative resource that could complement or substitute wood for this particular purpose (Mooney 2021). In coastal deserts, and particularly in Atacama, seaweeds and cacti are discussed as potential fuels (Zurro et al. 2021; Power et al. 2022).

Significantly, in the Atacama desert remains of burnt seaweeds have been found in fireplaces and in sedimentary deposits as a standard part of the archaeological record. In Northern Chilean archaeological sites, the employment of various seaweed species is commonplace for making pavements, fishing lines, or as components of mummification processes (Sitzia et al 2023 and references therein). Northern Chile archaeological record witnesses a standard use of seaweed for several purposes. These uses allow assessing the role of seaweed as essential for ancient habitation and cultural development in the area.

The complementarity of terrestrial and marine resources has been discussed as a general fact (Bailey 2004) and in relation to food supply (Tomczak 2003 and several others), however often limited to human-animal relations. This complementarity must be extended to the use of plant resources in coastal areas. Here, inland, coastal, marine plant and seaweed resources, are used in combination. In addition, in coastal systems, resource availability, technology, mobility, and population pressure each play specific roles, within an interpretative framework that acknowledges mixed economies as being far more complex than might be assumed a priori (Ahedo et al. 2021). In natural environments, the availability of terrestrial plants and marine resources depends on various factors, such as soil conditions, local geography, geology, water access, weather, climate, exposure to extreme events, erosion, seasonality, the accessibility to local flora, sea currents, morphology of the coast, tides, moon cycles, inter-annual oscillations like El Niño/La Niña southern oscillation (ENSO), evaporation, to name a few. These factors facilitate the accumulation of biomass or erode it. Moreover, many of these characteristics interact in non-linear ways, with dynamics difficult to capture and interpret. Simulating all these dynamics in a faithful way is probably still beyond state of the art and requires sizable multidisciplinary teams, combining modeling and measurements over many years, over a wide geographical area, using a wide array of instruments. Given the complexity of these interactions, accurately simulating a realistic scenarios is beyond the scope of our current work.

C. The fire from the sea model

The fire from the sea model, which we call seaFire, allows us to compare the consumption of land and marine fuels in the Atacama desert, with the goal to explore the use of seaweeds as backup fuel when terrestrial biomass is scarce. Beyond that, our case study of the Atacama coastline is just an abstraction of any scenario where dual fuel use might exist and there is relative scarcity of the preferred resource over the fallback one. We use the simplest possible modeling approach to assist on our interpretation of the archaeological and ethnographical evidence regarding seaweed use and diverse fuel uses.

To approach these marine terrestrial fuel dynamics, we use an agent-based model reflecting the switching between fuel use in a landscape. In the seaFire model we simplify fuel variability by generating random landscapes within a set range of values. On the temporal dimension, the evolution of the fuels themselves follow simple growth and depletion laws, which remain constant throughout the simulation. SeaFire thus reflects a variable environment while keeping the dynamics as simple as possible, making them easy to analyze in depth.

SeaFire conceptualizes how hunter-fisher-gatherer societies deal with the uneven distribution of terrestrial and marine fuels. The results allow us to assess the relevance of seaweeds as an enabler of population growth, cultural adaptability and mobility in the region. In environments when the easily accessible fuel – dry-wood and shrubs– is scarce, the use of less desirable fuel sources –seaweed accumulation on the coastline– will gain preeminence and be used as the main fuel source, at least for some periods of time. The availability of this secondary resource might influence mobility patters and its use informs the interpretation of the archaeological record.

With these general approaches, in order to capture the main dynamics of the use of land and marine fuels, we created a simplified representation of the costal stretch of the Atacama desert between $18^o2'S$ to latitude $22^o2'S$, covering about 400km. We simulated the differential use of terrestial-origin and marine-origin fuels: *Terrestial*, in the form of the limited biomass produced in the costal desert, and *Marine*, in the form of the abundant seaweed deposited and accumulated by the tides in some areas of the coastline.

In this landscape, agents (representing a group) move to first burn the terrestrial fuel available, and once depleted to minimal levels, the group starts making use of the marine fuel, until also depleted. Then the group moves to a new resource-full area. For seaFire, we consider each foraging area (cell) to be disconnected from the others, i.e. no other resources beyond the cell where the group resides is use. While this probably does not reflect realistic behaviors, were foragers are not limited to a strict range to pick up fuels, we limit this possible behavior to simplify our analysis.

D. Assumptions

Before describing the main features of seaFire, here we summarize the main assumptions we followed to build the Fire Form the Sea. We arranged the assumptions by two categories, *fuels* and *agents*.

1. Fuels Assumptions

- The landscape is inspired by the Atacama landscape, as narrow geographically bounded area, between the Cordillera de la Costa and the Pacific Ocean. We created our simulation as a row of land cells paralleled by a row of sea cells, in the form of an elongated rectangle (Fig 2, left side).

- The sea and land cells are not correlated, i.e. neighboring cells have fuel levels independent of eachother. While real-world landscapes typically exhibit correlations between nearby cells, seaFire simplifies this by assuming that the cells are uncorrelated. We consider this assumption the simplest, yet reasonable approximation for our purposes.

- Land productivity of fuel (terrestrial biomass) follows a logistic law. The productivity, therefore, is dependent on the presence of vegetation on the cell at each time step. The relative increase in biomass is constant for all cells. A logistic law is useful because it captures the natural growth of plants, initially fast when the biomass has been harvested for fuel, and then slowly approaching the caring capacity.

- Total land productivity is intentionally set to remain below the *Burning Rate* in order to prevent settled behavior. This design choice ensures that no single group becomes permanently established within a cell. If biomass accumulation over time exceeded the rate at which groups consume it, the simulation would result in sedentary populations. This outcome falls outside the scope of our analysis.

- We assume that seaweed in sea cells increases linearly at each time step. This linear increase is the same for all sea cells. In other words, the tidal deposition of seaweed is modeled as a constant process, determined solely by sea productivity common to all cells. Like for terrestrial fuel, the sea productivity is always below to what is consumed by a group.

- The maximum amount of marine fuel that can be accumulated at each cell is set initially and is different for each cell. This maximum amount can never be overcomes. This choice tries to reflect landscape characteristics where a specific stretch of coast can accumulate seaweed up to a limit, due to currents and geographical characteristics.

- There is no change on environmental factors over the simulation meaning that the maximum accumulation of fuels and fuel productivity is the same once it is initialized and until the sinuation ends. These values can change from simulation to simulation with different initial values.

2. Agents Assumptions

- Each agent in the simulation is considered to be a group of people collecting and sharing the fuel as a unit. We call this agent Hunter Fisher Gatherer Group (HFG). All of the groups burn fuel at the same ratio. Although there can be wide variability in burning rates depending on factors like local temperature, humidity, seasonal changes, and group size, for our fiducial model we considered the *Burning Rate* B to be constant throughout our simulations and for all agents. We set $B = 1$ to standardize and scale all resources to units of burning per group and time. This standardization imposes the condition that all our agents consume the same amount, independently of location, time, or any other considerations.

- The range of movement of a HFG group in one time step is limited by a range R. This is to capture the limited movement and range of foragers when moving camps.
- The number of HFG is constant throughout the simulation run. This assumption is the simplest, reflecting a stable density of HFG in the landscape. We consider that the landscape is at equilibrium, i.e. constant carrying capacity, and therefore the measure of relevance is the density of HFG, or number of HFG in the landscape.

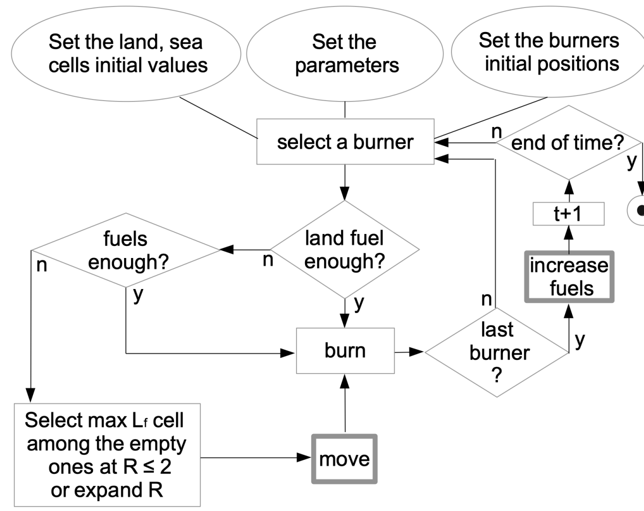

FIG. 1. Schema summarizing the main functioning of the simulation. The 3 big ellipsoids mark the setup of the simulation, while the small ellipsoid with a dot marks the end. Diamonds are decision making steps, with yes/no (y/n) answers, rectangles are actions. The two rectangles highlighted in thicker gray rectangles (move & increase fuels) are explained in expanded detail in the text.

II. SEAFIRE STRUCTURE AND COMPONENTS

Following the assumptions, we can separate seaFire in two parts, the fuels on the landscape, and the behavior of the agents. In figure 1 we present the schema of the simulation for a specific initialization.

A. Fuels in the landscape

For the landscape, we created a column of N land and sea cells. We summarize the land and sea cell parameters in table I and give their *fiducial values* and units.

Land cells are determined by three parameters: (i) L^{max} is *Maximum land*, the maximum amount of terrestrial fuel that that any cell can accumulate; (ii) L_p is the *land productivity* per unit of time; (iii) a fixed a minimum amount of fuel that is always present on any given cell (L^{min}), this parameter represents the remains of the biomass where new plants can grow. Moreover, each land cell is characterized by a fuel function $L_i(t)$, denoting *terrestrial fuel* at each time step, where $i \in [0, 43]$ and stands for the particular cell number.

Each sea cell is characterized by 2 parameters: (i) S^{max} is the maximum marine fuel that any cell can store; (ii) S_d is the amount of seaweed fuel deposited by the tides at each time step, called *sea deposition*. As with the land cell, each sea cell is characterized by a fuel function $S_i(t)$, denoting *marine fuel*.

The terrestrial-marine cell pairs (having the same index) also are defined by the presence of a HFG on them or not. In Fig. 2 we can see the different characteristics of the cell-pairs. The relative S_i^0 and L_i^0 levels vary for each cell-pair –top pannel: maximum marine fuel, marked by S_i^0, dotted blue line; and maximum terrestial fuel, L_i^0, dashed orange line. In 2, right, we highlight three representative cell-pairs. At the top panel, the maximum marine fuel is much higher than the terrestrial one. At the middle panel, instead is the maximum terrestrial fuel that is significantly bigger than the marine fuel limit. At the lower, the maximum amount of terrestrial and marine fuels are approximately the same (in units of group burning B).

To summarize, the cell-pairs are defined by:

- Initial maximum terrestrial fuel: L_i^0
- Land productivity: L_p
- Minimum terrestrial fuel: L^{min}
- Initial maximum marine fuel: S_i^0
- Terrestrial fuel function: $L_i(t)$
- Sea deposition: S_d
- Marine sea fuel function: $S_i(t)$
- Consumer presence: occupied/free

B. Setting of the simulation

We initialize all land cells with their maximum potential combustible values, denoted as L_i^0, where i identifies the specific cell. For the fiducial model, we assign to each cell i a maximum combustible value L_i^0. Initially, for each cell we randomly select a value uniformly from

L^{min} to L^{max}, thus $L_i^0 \in [L^{min}, L^{max}]$. We do the same for the sea cells, with $S_i^0 \in [S^0, S^{max}]$. This distribution of random values aims to capture the variability resources across the landscape. After this initialization of the cells, the fuels can never surpass the initial value, i.e. $L_i(t) \leq L_i^0$ & $S_i(t) \leq S_i^0$.

Then, we distribute the HFG randomly through the cells. Each HFG is assigned a cell i and no two HFG can be in the same cell at the same time.

We initialize each simulation with a set of fixed parameters, these parameters are fixed for a given simulation but vary from simulation to simulation (for example the number of HFG, or the maximum fuel). When we vary one parameter, we keep the rest of the parameters at their fiducial values, see table I. We represented this setting by ellipses in fig. 1). In table II we summarize the technical parameters of the initialization and running of the simulations, which are held constant for all the simulations presented in this work.

C. Running of a simulation

1. *Fuel's increase*

We model the increment of fuels for each land-sea cell-pair i.

Focusing on the land cell, we have chosen a logistic law to represent the growth of terrestrial fuel which logarithmically approaches carrying capacity, which we initialized as L_i^0. We codify this growth by:

$$\Delta L_i(n)(t + \Delta t) = L_p \left(1 - \frac{L_i(t)}{L_i^0}\right) \cdot L_i(t), \tag{1}$$

integrating L over t returns the general logistic form:

$$L_i(t) = \frac{L_i^0}{1 + e^{-L_p t}}, \tag{2}$$

where L_p is **Land Productivity**, it stands for the rate of increase of combustible for all land cells, per unit of time (table 1). We consider L_p to be a spacio-temporal constant; and L_i^0 defines *Maximum Land Resources* of the i cell i.e. the landscape can not accumulate more than a certain amount of fuel material. L_i^{max} can be understood as the carrying capacity of the cell in terms of fuel availability. L_i^0 is different for each cell, but it does not change once the simulation starts. Fig. 2, orange lines in each panel, show the logistic growth for tree different land cells having different L_i^0.

Focusing on the marine fuel, we describe the increase of marine fuel per unit of time. For this resource, we use linear dynamics, i.e. we grow the fuel by a constant amount per unit of time, until it reaches the maximum amount that a sea cell can contain. This maximum value is defined by S_i^0, as described. This simple behavior tries to capture the effects of tidal deposition on shore. At each tide the sea can deposit a certain amount of seaweed in a given spot of the coastline. When a spot is at maximum capacity, it can not hold anymore, even if the tides bring more, as we described in the assumptions. Fig. 2, blue lines in each panel, show the linear growth for tree different sea cells having different S_i^0.

We represent the marine fuel growth per unit of time as:

$$\Delta S_i(n)(t + \Delta t) = \begin{cases} 0 & \text{if } S_i(t) + S_d \geq S_0^i \\ S_d & \text{otherwise,} \end{cases} \tag{3}$$

where S_d is the sea deposition, or growth parameter of the marine fuel, as descrived. We can describe the evolution of the marine fuel over time with the general expression:

$$S_i(t) = \begin{cases} S_0^i & \text{if } S_i(t) + S_d \geq S_0^i \\ S_i(t) + S_d & \text{otherwise.} \end{cases} \tag{4}$$

Fig. 2, blue lines in each panel, show the linear growth for tree different values of S_i^0.

2. *Movement and fuel use of the Agents*

We modeled fuel consumption by the HFG movements. To simplify the modeling, the movements of these HFG are conditioned by fuel availability, as we describe below.

Three parameters define the agents: (i) the *number of HFG*, denoted as n_b; (ii) the **range of movement**, which represents the maximum number of cells that an agent can jump north or south to settle in a new cell and start burning, and is labeled as R; (iii) their **burning rate**, denoted as B, this value is equal for all the HFG, and is set to *1* for all the results presented in this work, all the units of the parameters related to fuel are in units of the *burning rate*. We summarize these parameters in Table I.

In Fig. 2 we can see in detail what happens to the fuels of tree representative cell-pairs depending on the presence or absence of a HFG. For the top panel, a HFG is initialized at that cell and it starts burning terrestrial fuel. Once the terrestrial fuel is not enough, it starts burning marine fuel. While the agent burns marine fuel, the terrestrial one is not used and starts recovering albeit initially slowly. Once both fuels are depleted, the HFG jumps to another cell and the initial cell-pair starts recovering both fuels. We can see that when the cell-pair is empty for long periods (for example in times between 200-280), the fuels grow to maximum levels. For the middle panel, the process is the same, but the maximum marine fuel is already really scarce in that cell, therefore it is not used much and the agent moves away after one or two uses. For the bottom panel, the cell-pair starts empty but after some time an HFG lands on it, and

TABLE I. Table enumerating the system parameters.

Symbol	Parameter Name	Fiducial	Units	Description of the parameter
B	Burning Rate	1	$[B/\Delta t]$	Baseline value of fuel burning for the group per unit of time, normalized to 1 to scale the rest of the parameters
n_b	HFG Number	8	[*n agents*]	The number of groups in the simulated landscape
R	Range	2	[*n cells*]	The maximum number of cells that a group can move in one time step
L^{max}	Maximum Land	5	$[B]$	Which is the maximum fuel to initialize land cells
L_p	Land Productivity	0.2	$[B/\Delta t]$	How much terrestrial fuel per unit of time is produced, on average, in a land cell
L^{min}	Minimum Land	0.1	$[B]$	Minimum terrestrial fuel that is found in any land cell
S^{max}	Maximum Sea	5	$[B]$	Which is the maximum fuel to initialize land cells
S_d	Sea deposition	0.4	$[B]$	Level of increase of marine fuel per unit of time in each sea cell

starts consuming the terrestrial fuel, then switches to marine, and then leaves, initiating the cycle again. As these three cases show, marine fuel recovers much faster and remains at top levels in the landscape for much longer, for the specific set of sea and land productivity in this simulation.

The rules dictating the HFG behavior are the following (as descrived in the central part of the Fig. 1):

- Each time step a HFG burns one unit of fuel B in the cell that it resides.
- First, an agent selects the terrestrial fuel, and if there is enough does not burn marine fuel.
- If there is not enough terrestrial fuel, the agent burns what terrestrial fuel is remaining, leaving a minimum L^{min}, and burns marine fuel until it has burned a unit B.
- If there is less terrestrial and marine fuels than needed in the cell-pair i, the agent moves.
- Each time a HFG moves, it will jump to the cell with the most fuel among the empty ones (not containing other HFG) within range R.
- If there are no empty cells within the range, the agent will increase the range and chose the cell with the maximum land fuel that also has enough combined marine and land fuels for satisfying the burning rate B,

3. seaFire Algorithm

After the descriptions of how the landscape and agents behave, we can summarize seaFire in a simple algorithm, which we also graphically illustrated in Fig. 1):

1. Set the model parameters from a configuration file.
2. Initialize the landscapes creating N sea and fuel cells with random maximum fuel values between $0 : S^{max}$ and $L^{min} : L^{max}$ respectively.
3. Initialize n_b agents through the cells.
4. Start a run of the model (a simulation) with $t = 0$
5. If a HFG is in cell i and $L_i(n) > B$ then reduce the amount of *terrestrial fuel* by a unit of consumption $L_i(n+1) = L_i(n) + \Delta L_i(n) - B$.
6. If a HFG is in cell i and $B > L_i(n)$, the agent burns *marine fuel* $S_i(n) = B - \Delta L_i(n) + L^{min}$.
7. If $L_i(n) + S_i(n) < B$, the HFG moves to a cell with the maximum L within a range R among the empty ones.
8. If there are no empty cells around the agent, or these have not enough fuel, the Range increases by one unit, until a cell satisfies the fuel needs. If several cells satisfy it, the HFG moves to the one with maximum terrestrial fuel.
9. Once the agent has moved, it consumes the fuel where it has landed.
10. Once all the HFG have either burned fuel or moved & burned, time is increased by one unit and the fuels are increased: *Terrestrial fuel* growth of each the cell by $\Delta L_i(L_p,\, L_i^0,\, L_i(n))$. *Marine fuel* increases in each the cell by $\Delta S_i(S_d,\, S_i^0,\, S_i(n))$.
11. Once the time set for the simulation is reached, the simulation ends. At each time step we store the total amount of fuels present at each cell, the agents positions and the maximum range moved by an agent.

III. RESULTS

Here we present the main results of the work, which show the proportion of fuel type (terrestrial vs marine) used on average per agent at the end of the simulation and mobility patters. These analysis allow us to explore under which circumstances a fuel is used the most and how the presence of the fall-back fuel in more or less abundance might influence movement through the landscape.

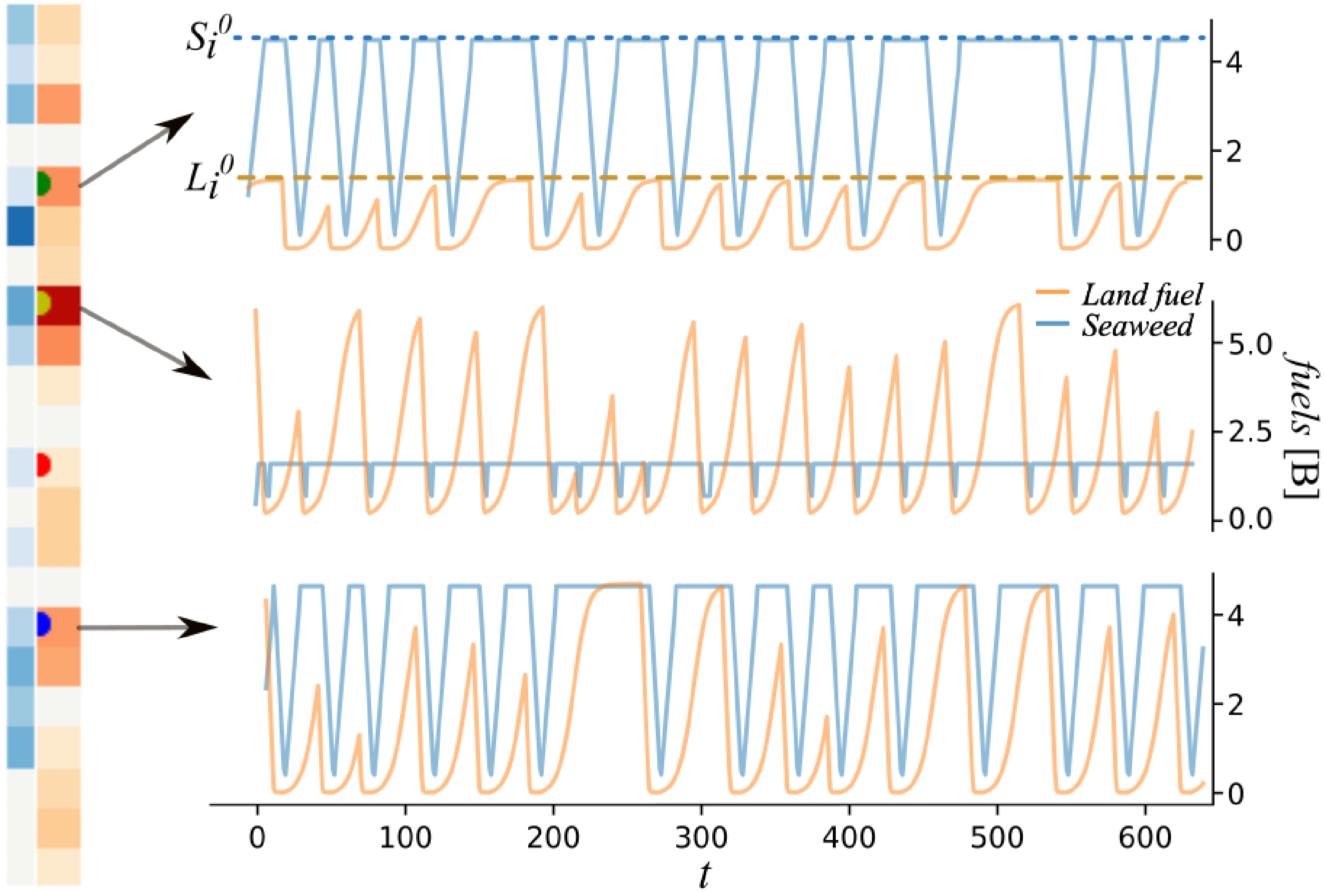

FIG. 2. Landscape and fuel series representation. On the left we show the first frame of a reduced simulation, with only 22 cells and 4 agents. Each agent is represented by half a colored dot. The orange rectangles represent the amount of terrestrial fuel at each time step, the darker orange the higher the amount of fuel. Similarly, the blue rectangles represent the marine fuel level. As seen, the fuel levels are distributed randomly through the cells. On the right there are 3 time series of the fuel levels for 3 different cells where the initial values L_i^0 (dashed orange line in the bottom plot) and S_i^0 (dotted blue line in the top plot) are different for each of them, dictating their different fuel dynamics when the HFG visit them and recovery when they leave. In the supplementary materials you can find a *gif* file with a short movie of the simulation. For this figure the parameters are

A. Fuels Used

For our analysis, we focus on the burning of fuels by our HFG. We first compute at each time step the amount of marine fuel burned by the agents, as illustrated by Fig. 3. The thin orange line denotes the total terrestrial fuel burned at each time step by all agents, the thick orange line is a running average of this value for visualization reasons. The thin and thick blue lines represent the same for marine fuel burned. In this particular simulation setting, we can see how the use of marine fuel is consistently higher than the use of the terrestrial one. As we would expect in the Atacama case, the land productivity is relatively smaller than the sea one.

Then, at the end of each simulation run, we sum the total amount of sea resources consumed by our agents, after discarding the first c steps. We discard these initial steps because is the time that the simulation needs to be in equilibrium. As seen in fig. 3, after about time 30, the burning of fuels stabilizes. The average of land resources burned in our simulation normalized by the length of the simulation and number of HFG is:

$$L_a = \frac{\sum_k^T \sum_j^{n_b} l_{jk}}{T \cdot n_b}, \tag{5}$$

where l_{jk} is the amount of terrestrial fuel burned by each agent j at each time step k, and T is the total time being considered. We do the same for the marine fuel:

$$S_a = \frac{\sum_k^T \sum_j^{n_b} s_{jk}}{T \cdot n_b}. \tag{6}$$

Once a simulation finished, we store its L_a and S_a values.

TABLE II. Table enumerating the simulation parameters.

Symbol	Parameter Name	Fiducial value	Description of the parameter
N	Number of Cells	44	The number of cells
T	Time of the Simulation	240	How long the simulation runs, in tics
c	Cut Interval	30	Initial time not considered for the analysis, because the simulation is not in equilibrium
L_i^0	Land's Initial Conditions	$[L^{min} : L^{max}]$	The distribution of land resources is set randomly, with no correlation between cells. The values are initialized at the beginning of the simulation and range from L^{min} to L^{max}
S_i^0	Sea's Initial Conditions	$[0 : S^{max}]$	The distribution of sea resources is set randomly, with no correlation between cells. The values are initialized at the beginning of the simulation and range from 0 to S^{max}
P_0	Agent's Initial Positions	$[0 : 43]$	The agents start the simulation with their positions set randomly

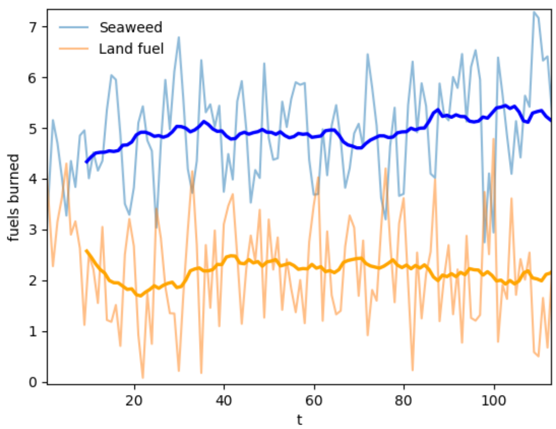

FIG. 3. Summed fuel burned per unit of time for one time series. In orange we show the initial terrestrial fuel burned per unit of time, with the thick smooth line being the running average over 20 units of time for visualization reasons. In blue we do the same for marine fuel. The figure represents a time series with 8 HFG, 44 cells, $L_h = 5$, $S_h = 4$, $L_p = 0.4$, $S_d = 0.4$.

B. Mobility Strategies

We present a simple analog Atacama landscape, and how different tidal depositions of seaweed on the sea cells might shape the mobility strategies for different densities *(numbers) of HGF. For that we chose the lowest end of the land productivity, $L_p = 0.05$ and simulated two scenarios, one with middle tidal deposition, $S_d = 0.15$, and one in the high end $S_d = 0.45$.

We show the results in Fig. 4, where we present the average movement per agent and time (top) and the maximum range of movement (bottom). To produce the panels we made 33 runs of the simulations and plotted the average (thick lines) and maximum and minimum realization values (shadow envelope).

First, we focus on the average movement (top, magenta), and its envelope (shadow area representing the maximum and minimum values). An average movement of 0.1 means that, on average, an agent moves once every 10 time steps, or that 10% of the agents will move on that time step. An average movement of 0.5 means that every 2 time steps the agent moves, or that half of them move. This is the maximum we expect for seaFire because that means that they only burn one unit of fuels (B) after they move, and then they need to move again.

We remind that the Fiducial model has 44 cells, so the maximum $n_b = 22$ means that there is one agent every 2 cells. In other words, there are on average two foraging ranges per HFG. We consider this limit to be an extreme, and probably not reflecting a reality on the landscape, but it is interesting for visualizing the dynamics of the model in extreme cases.

For the *high* case (dotted line), initially the increase is slow for all range of HFG number, but it is probably non-linear, with slower increase at the begging, until about 10 agents, and a steeper slope after.

For the *medium* case (dashed line), we see how for increasing HFG number (n_b), the movement sharply increases in a non-linear way, making an S shape. Also, like in the *high case*, the increase is slow until HFG is about 10, and then increases rapidly until it flatters at about 18, with a small decrease after. By $n_b = 18$ the average movement almost reaches its 0.5 maximum. We will see why they do not increase the average movement to the limit (0.5) when we show the maximum range results.

Now, we focus on the maximum range a HFG travels to forage for fuel (Fig. 4, bottom, brown). Fist, we emphasize that this is the *maximum* range, which does not mean that all the agents have the same range at all the time. Just some agent, at some point of the simulation, has had to move all that range to access the needed fuels. The values of the maximum range are normalized by the number of cells, or the landscape size to show how the range length is relative to the whole landscape. A value of 1 means that the agent has a range as big s the whole landscape. On the other hand, a range value of 0.1 is the minimum range, set to the Fiducial $R = 2$ value. In this panel we see a similar non-linear dynamic following an S shape. Although, on first approach, the range dynamics

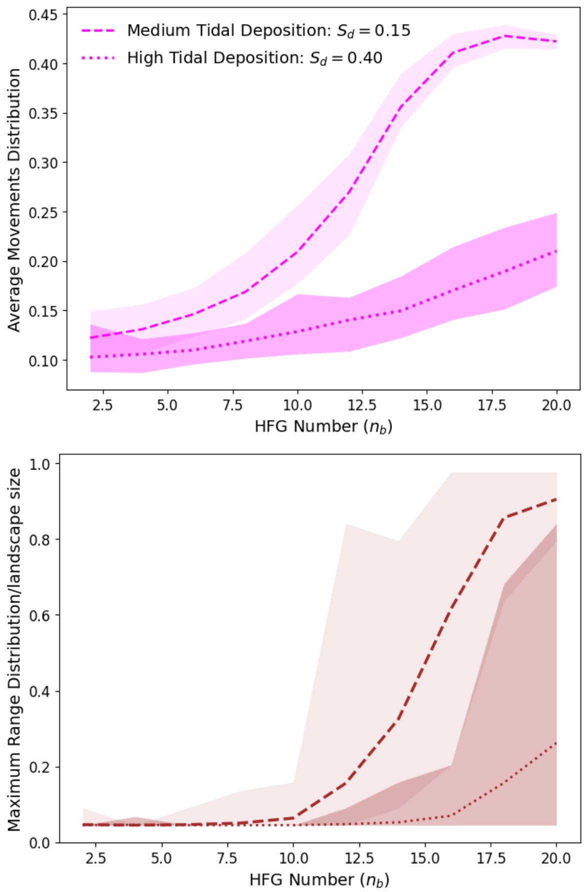

FIG. 4. **Mobility outcomes for two sea productivity scenarios in an dessert landscape.** Average movements and maximum range of movement for two different tidal deposition (marine productivity). Both cases (medium $S_d = 0.15$, dashed line, and high $S_d = 0.45$, dotted line) are for a scenario with scarce land productivity ($L_p = 0.05$). *Top panel* represents the average movement and envelope (maximum and minimum values) per agent and time step for 33 different simulation runs. For example, a value of 0.2 means that, on average, an agent moves once 5 time steps, a value of 1 means that it is moving every time. Dashed line and transparent magenta shade represents the medium sea productivity scenario, while the dotted line, darker magenta shade represents the high sea productivity. *Bottom panel*, same as top but in brown, representing the maximum range that any agent has moved in one run of the simulation, normalized by the landscape size (number of cells $N = 44$). For example, a value of 0.05 means that the movement is the default range $R = 3$, a value of 1 means that the agent has moved across all the length of the landscape.

seem to follow the average movement ones, they differs on critical aspects, which explain the average movement not being maximum for high HFG numbers.

For the *high* case, the range starts increasing noticeably only for HFG numbers higher than 16. For the lower end, that means that the agent on average stays on the standard range area (2 cells up or down from the HFG is). However, when the density increases, the cells around the agent might be full, or the fuel levels not be enough, therefore, as seaFire is set, the range starts expanding, until the agent can move to a place with enough fuels, and containing the most terrestrial fuel within that expanded range, or until the maximum range is equal to the landscape length.

For the *medium* case, range starts increasing significantly HFG numbers bigger than 10 until it flatters at about 18 agents. When the agents are maximal, the maximum range is mostly equal to the landscape length. That means that at least some agent has moved all the way to the other extreme of the landscape (at least once). In this scenario fuels are so scarce that the best strategy to find the needed fuels is to traverse the whole landscape in order to secure the needed fuel. We remind that this is just a model and we are just exploring the extreme values of the parameters. We will expand on the meaning of these results on the discussion.

The observed increased movement and then expansion of range strategies for higher HFG number explains the movement vs maximum range dynamics. First the agents start moving more on average, then the maximum range also increases (at least some times for some agents). The increase on range optimize the access to the fuels needed, as the landscape starts to be depleted faster. In this case first HFG might need to travel more often. Then, some agents need to travel further to have access to the needed fuels.

Interestingly, for different levels of tidal depositions (*high* vs *medium*), the movement strategies can be easily distinguished for HFG numbers above 9 or 10. Similarly, the long-distance displacements conducted by some agents is significantly different for both scenarios, whit little overlap even of the envelopes for high agent densities ($n_b \leq 12$).

The non maximal movement (and small decrease) for the *medium* tidal deposition case can be explained by this maximum range expansion. If more an agent agents expands the maximin range, it moves to the most optimal spot of the landscape (i.e. maximum range = 1). In this large-distance cases, on average, the agents need to move less, as the cell selected might provide enough fuels for longer times, instead of moving to a sub-optimal cell which is closer but that needs to be abandoned sooner. In the discussions we will analyze in detail the contrast between of the benefits of longer ranges vs fewer movements, or the contrary, more frequent displacements vs shorter distances.

C. Consumption and mobility for parameter ranges

Once we have shown the different mobility strategies that arise from our model for two different landscapes with more or less marine fuel and different HFG densities, we can do the same exercise but for all the combinations of parameters. For that we explore how the HFG number

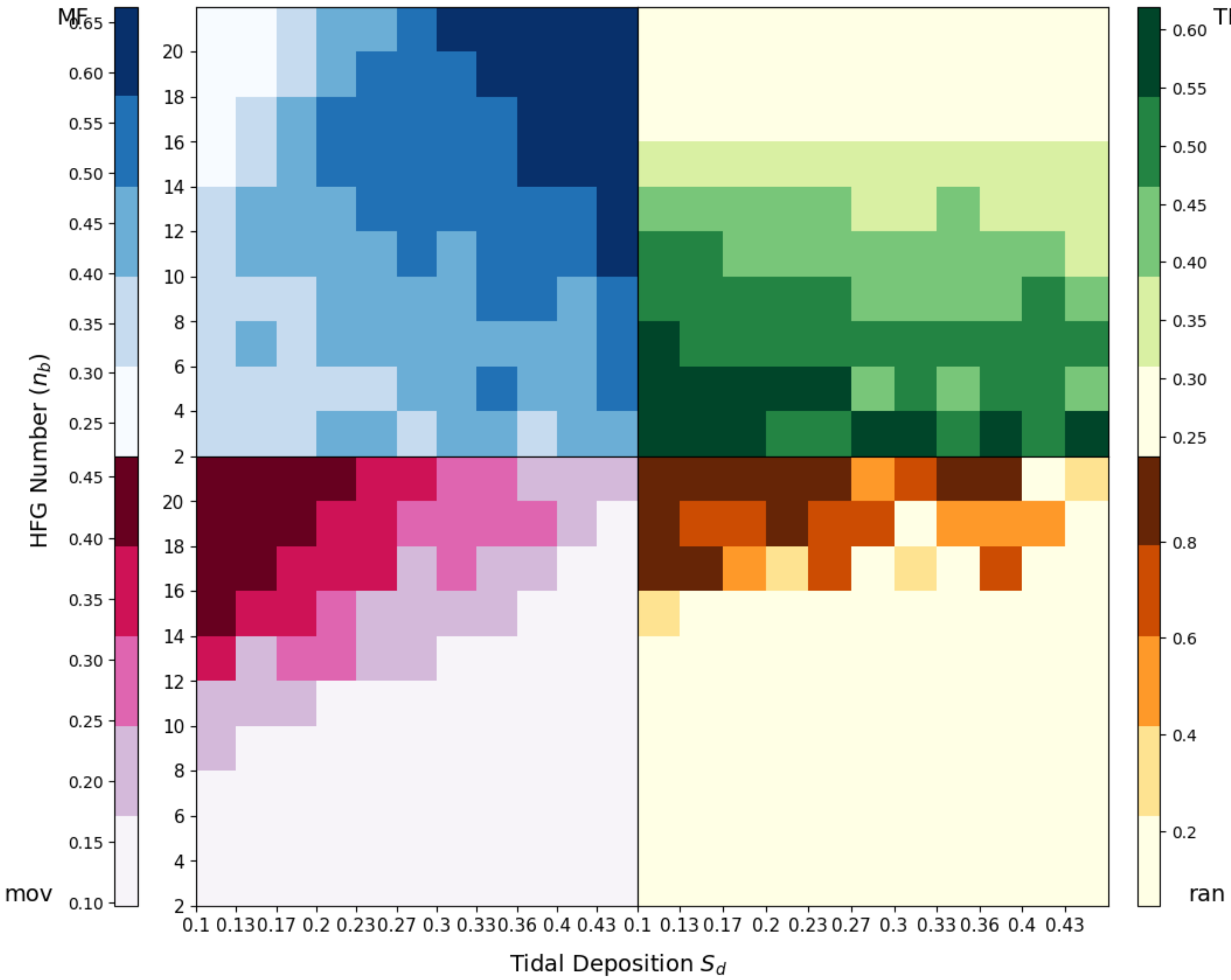

FIG. 5. **Different fuel use and movement strategies for different tidal deposition rates and number of HFG in the landscape.** The four panels show the relative use of marine (MF) and terrestrial fuels (TF), average agent movement (mov) and maximum range (ran), respectively. We show these values for each combination of number HFG (n_b) and tidal deposition (S_d), with all the other parameters set to Fiducial values shown in table I. The ranges are $n_b \in [2:22]$, y-axis, and $S_d \in [0.1:0.44]$, x-axis. In Blue shades we show the average use of marine fuel per agent and time. For example, if MF = 0.6, means that, on average, an agent uses 60% or more marine fuel, if 0.1 that means 10% of marine fuel. In Green shades we show the average use of terrestrial fuel per agent and time. The shades mean the same as the marine ones, but representing terrestrial fuel use. In purple shades we show the average movement per agent and time. In brown shades we show the maximum range of the an agent in the simulation run. The units for the purple and brown panels are the same as explained in Fig. 4.

(n_b) consumes the fuels for different values for the four main landscape characteristics: land productivity (L_p), maximum terrestrial fuel (L^{max}), sea deposition (S_d) and maximum sea cell fuel (S^{max}). Each time we modify a pair of parameters we keep the others constant at the fiducial value (shown in Table I).

We show our results in Fig. 5 for a grid of two parameters: number of HFG n_b, and tidal deposition S_d. For each pair of these parameters, within a set limits $n_b \in [2:22]$, $S_d \in [0.15:0.45]$, we computed four outcomes: (MF), average marine fuel consumption per agent and time, S_a (Eq. 6, Fig. 5, blues); (LF), average terrestrial fuel consumption per agent and time, L_a (Eq. 5, Fig. 5, greens); (mov), average movement per agent and time (Fig. 5, magentas); (ran), maximum range of an agent in the simulation (Fig. 5, browns). We plotted each of these values for each combination of parameters by varying them in pairs. Then, plotted that in one square of the grid.

If we focus on Fig. 5 MF, we see that the blue colors range from about 0.1 to about 0.7. For a value of 0.7 means that, on average, an agent burns seaweed accounting for 70% of its fuels needs. That means that the rest of the fuel burned is terrestrial biomass. As it is expected, the higher the HFG number, the higher stress on the fuels and more dependence in sea resources. Also, as expected, when the tidal deposition rate is higher, the agents will make more use of marine fuel, as is seen in the top left corner of the blue panel.

If we focus on Fig. 5 LF, we see that the green colors also range from about 0.1 to about 0.7. Similarly, for a value of 0.7 means that, on average, an agent burns terrestrial fuel accounting for 70% of its fuels needs. The rest will be the fall-back resource, or seaweed. As it is expected, this panel is mostly the opposite of the MF one, but not completely, as in the top-left corner of both MF and LF we see that the average fuel burned are not opposites, both fuel levels burned are low, as it is expected because both fuels are scarce in a densely populated landscape, with high HFG numbers. That means that an agent has to move on average more to satisfy the fuel needs.

We see the increased average movement on Fig. 5 (mov). The magenta colors reflect the same as seen in Fig. 4 (top), but for 10 different values of tidal deposition (S_d), instead of 2. As expected from Fig. 4, the top-left corner has an increase of average movements per agent, especially pronounced for low levels of tidal deposition. This shows that, even with out simple model, agents can explore another strategy. In seaFire terms, that means that the HFG burns whichever fuels are left on the cell, and then moves. If the movement is frequent, it means that, on average, less fuel is burned, as is seen by the fact that the combination of the MF and LF is less than 1 for the top-left corners cases.

Finally, as with figure Fig. 4 (bottom), in Fig. 5 (ran) we plot the maximum range that a HFG has moved in a simulation. As with the 4 case, when agent density is high, the maximum range can increase substantially, even for elevated tidal deposition values. This seeking for fuels is aligned with increased movements, but as we already highlighted on the previous subsection, the increased range explored might make the agents more settled, on average, as the cell selected allows for longer stays in that cell. This long-range movement will be a fourth strategy available to the agents (in the extreme of the parameter range).

In the discussion we will analyze the meaning of these results in the context of four main strategies of fuel management and movement through the landscape for Hunter-Fisher-Gatherer groups.

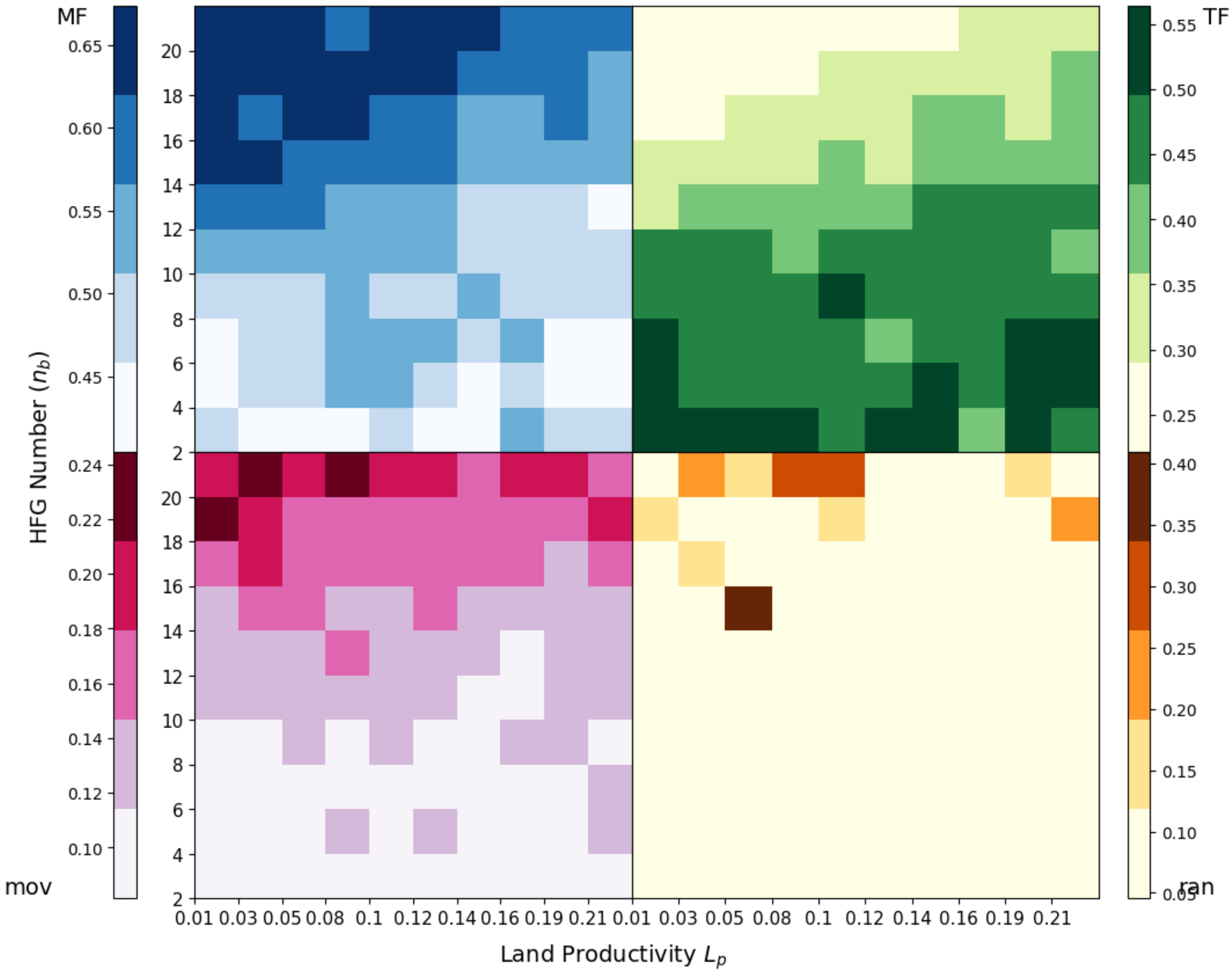

FIG. 6. **Different fuel use and movement strategies for different land productivity rates and number of HFG in the landscape.** The plot follows the same patter as Fig. 5, but for different values of land productivity ($L_p \in [0.01 : 0.22]$, x-axis) while keeping the rest fixed to fiducial values. In particular $S_d = 0.4$ for all the results in this figure.

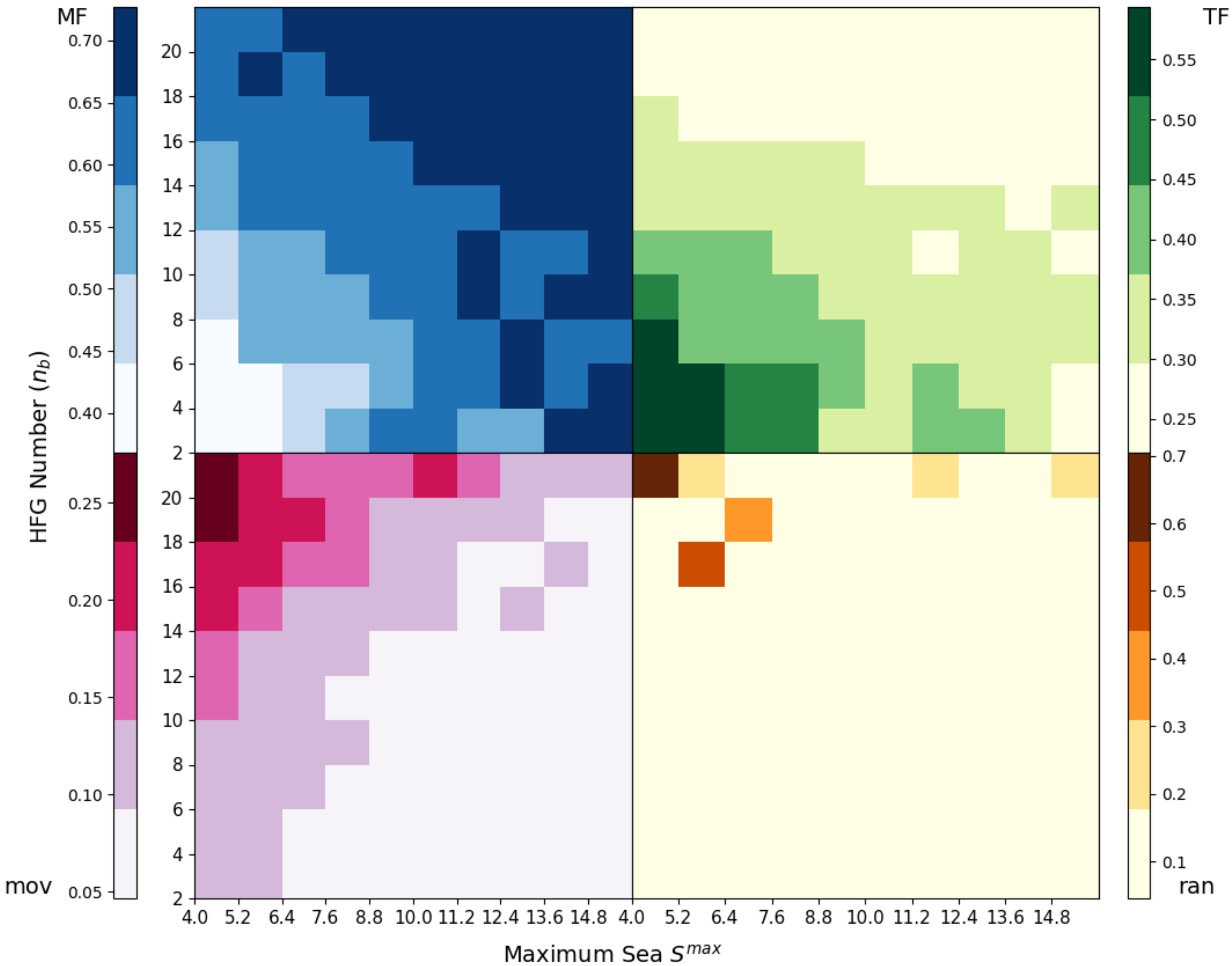

FIG. 7. **Different fuel use and movement strategies for different maximum marine fuel available and number of HFG in the landscape.** The plot follows the same patter as Fig. 5, but for different values of maximum accumulation of marine fuel in the sea cells ($S^{max} \in [4 : 18]$, x-axis) while keeping the rest fixed to fiducial values.

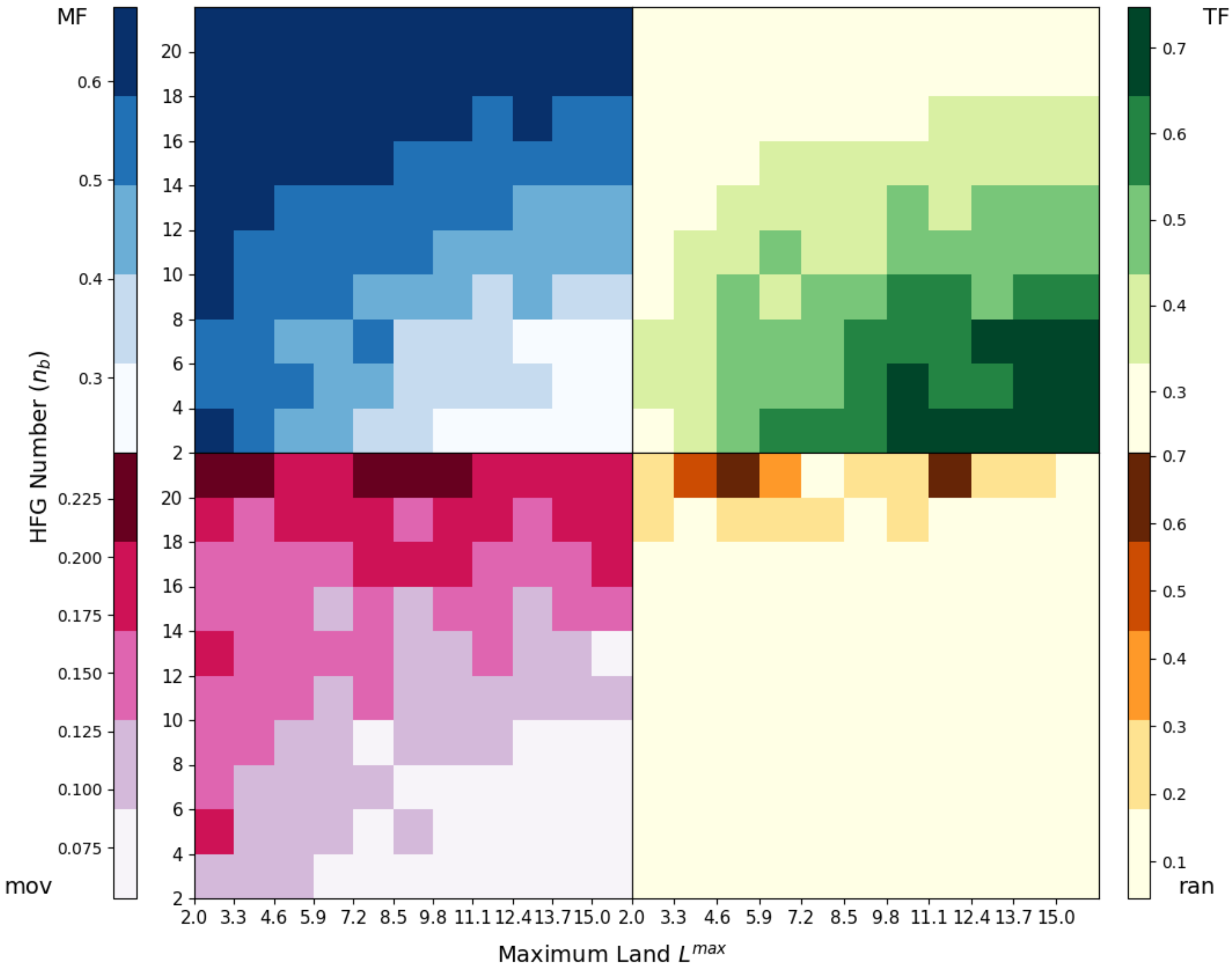

FIG. 8. **Different fuel use and movement strategies for different maximum terrestial fuel available and number of HFG in the landscape.** The plot follows the same patter as Fig. 5, but for different values of maximum accumulation of marine fuel in the sea cells ($L^{max} \in [2 : 16]$, x-axis) while keeping the rest fixed to fiducial values.