The Cardial Spread Model
By
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OVERVIEW

Purpose
Four conceptual models have been proposed to explain the spread of the Impresso-Cardial Neolithic in the west Mediterranean. The purpose of this model is to provide a platform to test and compare multiple hypotheses for the spread of the Neolithic in the west Mediterranean. The model includes farmer village agents and forager band agents which occupy individual patches. Farmer agents found new agricultural villages (new Farmer Agents are created) when the population of a village reaches its carrying capacity or by random chance (dependent upon the model being tested). Forager agents may become farmer agents, a process which is initiated by different rules within a conceptual model. The agents are located on a GIS (Geographic Information System) based landscape which incorporates a map of the west Mediterranean (Italy, southern France, the Iberian peninsula and the northern coast of Africa). Multiple maps of environmental factors can be chosen at the onset of the simulation. Farmer agents use the information from these maps to inform their choice of location for new agricultural villages. As the simulation progresses, farmer agents spread to new locations and the timing of the arrival of agriculturalists to a region is recorded. Once the simulation has ended the timing of agricultural arrival is compared to the arrival of agriculturalists as evidenced in the archaeological record. Through this process, multiple hypotheses of agricultural spread can be compared to one another and their relative success in explaining the spread of the Neolithic can be assessed.

State Variables & Scales
The agent-based model is composed of two agent types: farmer agents and forager agents. The farmer agents represent an agricultural village and have a village population, and may have social links to neighboring foragers. Forager agents represent forager groups; they have a group population and may control multiple patches that represents a forager group's range. The model is set on a yearly scale and records the year starting from the earliest radiocarbon date recorded for southern Italy.

Agents are located on a digital landscape created by importing a map of the west Mediterranean. The map includes an environmental factor that agents bay use to evaluate the patches around them when they wish to move. Maps were created using the GRASS GIS from modern topographical information and/or modeled paleoclimate datasets.

Process Overview and Scheduling
Each time step in the model represents a year. During this year, each farmer and forager agent adjusts its population based upon birth and death rates. If a farming village nears its carrying capacity, a new farmer village may be established and a portion of the village's population moves to a new village. Forager agents may adopt agriculture (from several

different factors) and in these instances farming villages are established on locations that made up the forager's territory and the forager population is split equally among these new villages (farmer agents). If a farmer agent has reached the carrying capacity of a patch and there are no new locations for an agricultural village to be established, then that farmer agent becomes inactive. The arrival year for the founding of each new village on a patch is recorded for each patch.

This equation represents when farmer villages decide that some of their population must leave to form a new village.

if Village Population > [(Max Farmers Per Patch) * Farmer Carrying Capacity Threshold]

if Village Population > [(Maximum Farmers Patch) * Proportion of Farmer Village Fissioning]

Design Concepts

Emergence: This model is designed to study the spatial patterns of Neolithic spread in the west Mediterranean. The chronological and locational information for the spread of the Neolithic is compared to a map of the spread of the Neolithic created from radiometric dates located within the study area.

Interaction: In the implementation of the Capillary and Dual models, interaction is simulated along social networks. Each year, farmers and foragers interact and as these interactions increase, so does the likelihood of a forager agent adopting agriculture and becoming a farmer agent.

Sensing: Agents are able to sense the landscape value of the patches surrounding them within a given range. Agents are also able to sense if these patches are occupied. Agents connected within a social network are also able to sense each other's presence and the type of agents they are (forager or farmer). The networks can occur in three configurations. One configuration favors links with forager nearby, one with foragers far away within a given radius and one is random.

Stochasticity: A large number of processes are stochastic in nature. Although agents prefer to move to the patch with the highest land value, agents may randomly choose between patches of the same value. The frequency of agricultural spread in the capillary model is determined by random chance as is the frequency of maritime movement in the Maritime Pioneer Colonization model. Network connections are also made randomly within a geographically bounded region. Population variables (birth and death rates) are also simulated with random chance. To understand this stochasticity, each combination of parameters was run 1000 times and then random samples of different sizes were compared to those results to determine if a significant difference existed between smaller samples and the full 1000 model runs. This process is detailed in chapter 5 of this dissertation.

Observation: As agriculture arrives on each patch for the first time, the simulation year is recorded for that patch. At the end of the simulation, a map of the arrival of agriculture is output as a map. This map is then compared to a map of arrival times from the archaeological record using a regression between the two maps.

Initialization

Most of the parameters used to initialize the model can be changed by the user since most of these parameters are unknown to archaeologists. A map (chosen by the user) is read into Netlogo and values from the map are used to designate land / ocean and the relative value of land patches. Another parameter chosen by the user is the location and density of forager agents. Foragers are initialized at random locations throughout the model and the number of them depends on the density chosen from the menu at the beginning of the model. One farmer village starts in southeastern Italy – and this agent originates the spread of the Neolithic.

Input

The land value which agents use to evaluate where to move is based upon a map imported into the simulation when it begins. The paleoenvironmental maps were constructed from modern topographic and modeled prehistoric paleoclimate data. The maps were created in GRASS GIS and are based on paleoenvironmental data. For a full description of how these maps were created see Chapter 3 of this dissertation. A table of the equations used to create each map is included below.

Submodels

The focus of this agent-based model is the evaluation of four main conceptual models proposed for the spread of the Neolithic in the west Mediterranean. The relative comparison of these conceptual models is the primary focus of this computational model. Most of these models are composed of elements from the other models since they conceptually build upon one another.

The Wave of Advance Model

In the Wave of Advance model (WA), farmers move to neighboring patches when they have reached a population threshold. The threshold is determined by the size of each patch and the subsistence strategy of a farmer village. Once the population threshold is reached a farmer village moves to a neighboring patch that is unoccupied and has the highest land value (determined from the imported map). Although the village is 'moving' to a new location, in this case a new farmer agent is created. If two patches have the same land value, then one is chosen at random. This process continues until no new locations can be occupied or the simulation runs out of time. It is an implementation of Ammerman and Cavalli-Sforza's model (1984). A schematic of this process is reproduced from Chapter 5 and is included below.

The Leapfrog Model

The leapfrog model is an extension of the ideas used in the Wave of Advance model. Farmer agents move and found new villages in patches as a result of the agent's population reaching the carrying capacity for a patch. New villages, however, may be established within a given range of the parent village instead of only neighboring patches. A schematic of this process is reproduced from Chapter 5 and is included below.

The Capillary Spread Model

The Capillary Spread model is an implementation of the model outlined by Vicent Garcia (1997). In the implementation of this model, all of the forager agents are connected to one another by network links. The structure of this network is constructed according to a user selected rule set. The links may be random, may favor local connections or may favor distant connections. The farmer village which is inserted at the beginning of the simulation is also connected to these forager agents through a social network. Each year, the populations are updated and agriculture has a random chance of spreading along network connections from an agricultural village to a farmer village. Each farmer village may spawn and spread new farmer villages in the same manner as the leapfrog model. A schematic of this process is reproduced from Chapter 5 and is included below.

The Maritime Pioneer Colonization Model

The Maritime Pioneer Colonization Model (MPC) is an implementation of the conceptual model put forth by Zilhão (2001). Farmer villages may expand by way of a leapfrog spread when they are located in non-coastal areas. Farmer villages that are located along the coast may move long distances along the coast to establish a new village. While this movement is also triggered by a farmer village reaching its carrying capacity, carrying capacity is best kept lower to better represent the MPC model. As described by Zilhão, farmers may have migrated to new villages before reaching ecological limitations because of social factors. Since social factors are often related to population, carrying capacity limits were still used. A schematic of this process is reproduced from Chapter 5 and is included below.

The Dual Model

The Dual Model is the most complicated of Neolithic spread mechanisms and was first outlined by Bernabeu Aubán (1997). Forager agents are connected to one another with a social network as was described for the Capillary model. Farmer agents use leapfrog and maritime spread as they did in the MPC model. Forager agents that are nearby farmer agents have a chance to adopt agriculture that increases as the length of interaction increases (direct neolithization). Also, forager agents that are connected to forager agents that are interacting with farmer agents also have a chance to adopt agriculture (indirect neolithization). A schematic of this process is reproduced from Chapter 5 and is included below.

The original model description and results are presented in this Dissertation as well as

2016. Neolithic Spread Models, Agricultural Islands and Pivotal Parameters: Impressions Gleaned from Simulating the Spread of Agriculture in the West Mediterranean. Paper Presentation at the 81st Annual Meeting of the Society for American Archaeology in Orlando, FL.

2015. Modeling the Influx of Agriculture: An Agent-Based Model Exploring Agricultural Spread Scenarios in the Western Mediterranean. Poster Presentation at the 80th Annual Meeting of the Society for American Archaeology in San Francisco, Ca.

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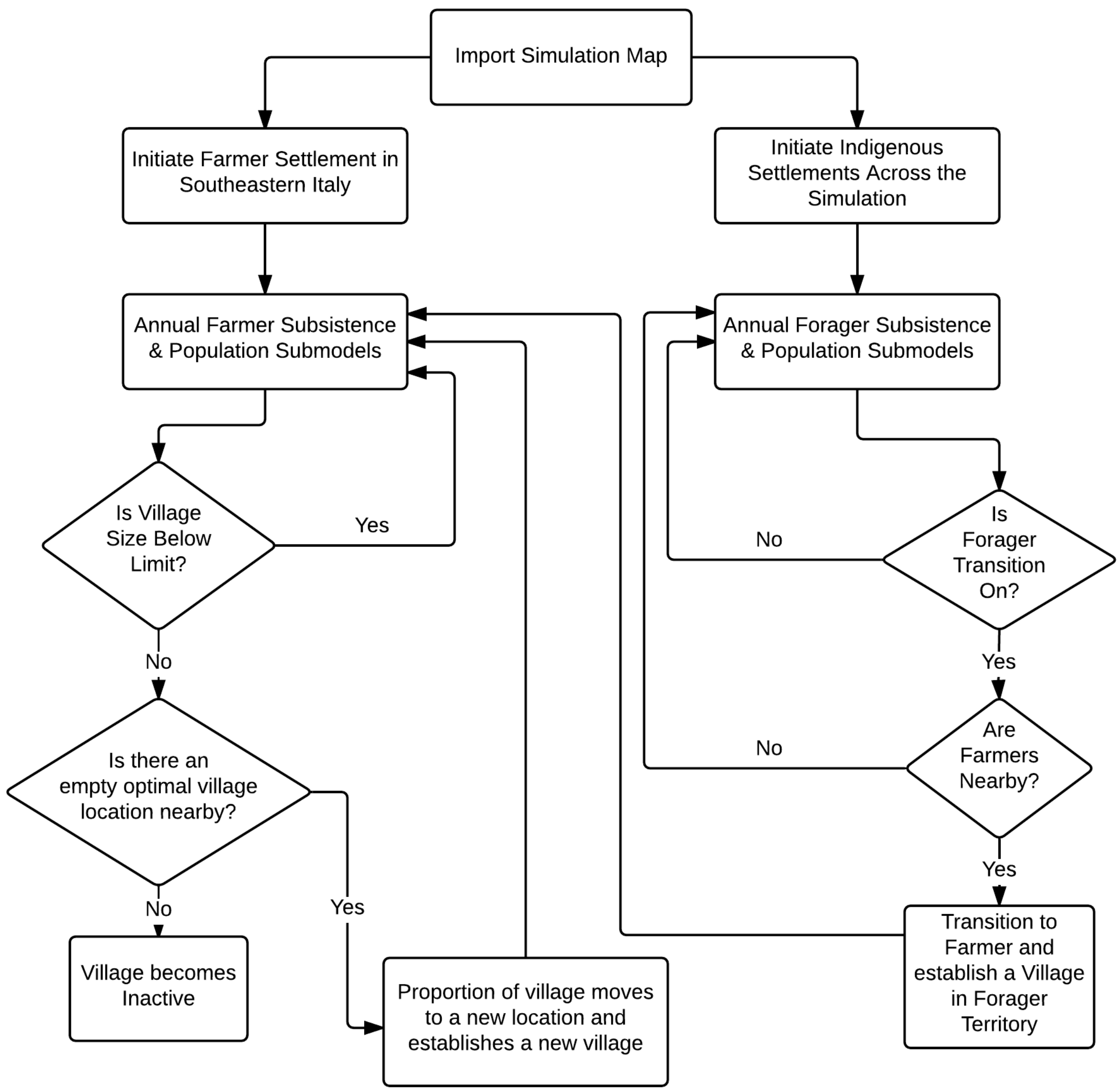
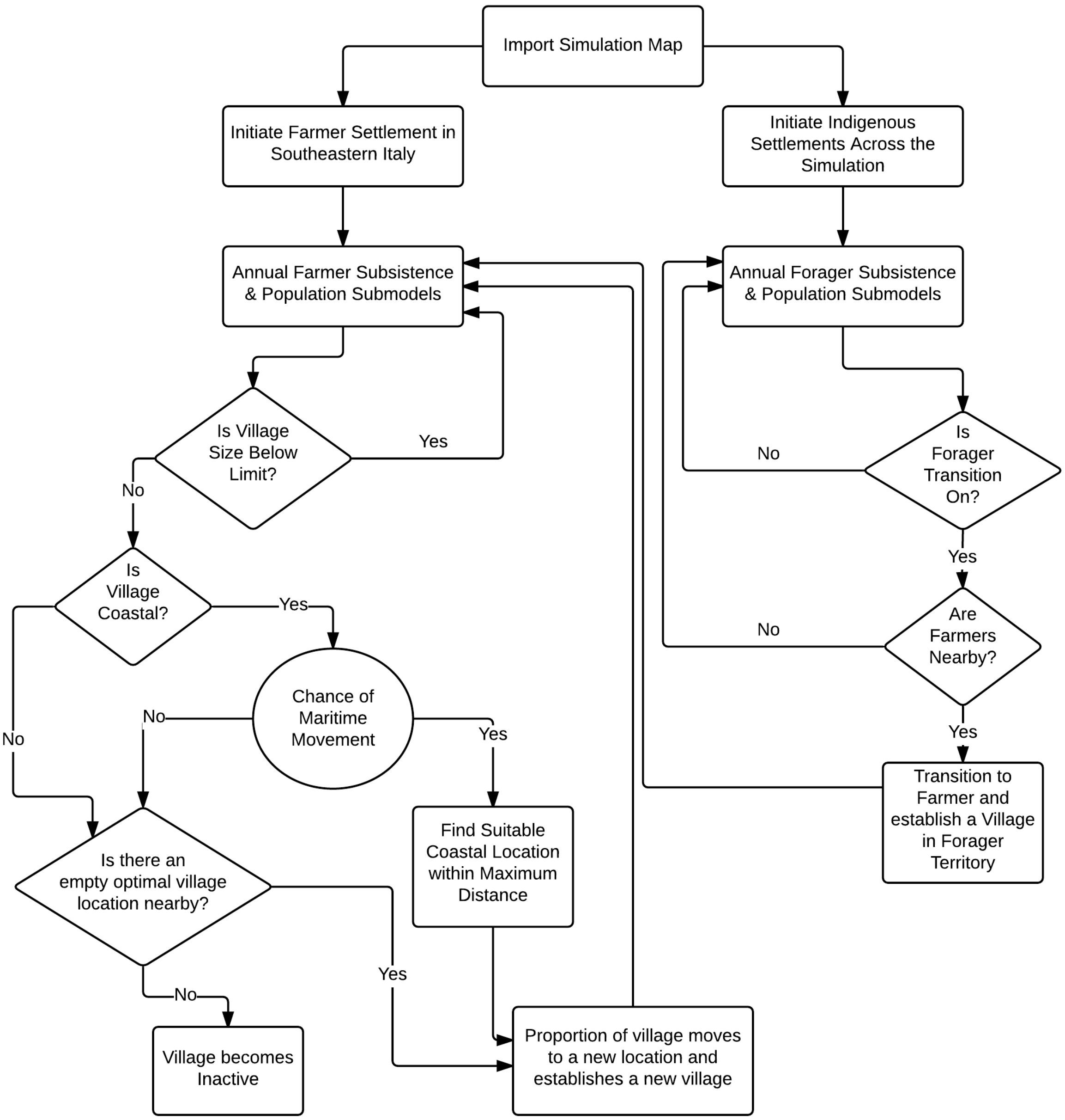
MAP TYPE	FORMULATION INFORMATION
Slope	Created using the r.slope.aspect module in GRASS GIS from 90m x 90m SRTM data. Slope Map = 100 - Actual Slope (this creates a value from 100 - 0 to rank low slopes higher)
Spring Precipitation Sum	Created from PMIP 3 data. Spring Precipitation = March Precip + April Precip + May Precip
Slope & Annual Average Precipitation	The annual average precipitation is calculated from PMIP 3. Annual Average Precipitation = (January Precip Total + Febraury Precip Total + … December Precip Total) / 12 Reclassified Annual Average Precipitaiton = if map value lies between μ - **σ** and μ + **σ** then map value = 75, else map value is 50 Slope & Annual Avg Precipitation Map = (Slope Map + Reclassified Annual Average Precipitation) / 2
Minimum March Temperature	Initial temperature values created from PMIP 3 data. Reclassified the Map: if map < 0 then map = 0; if map = 0 or map = 1 then map = 50; if map = 2-4 then map = 75; and if map > 4 then map = 100
Best Wheat Locations	This map combines four maps, a slope map, a spring precipitation map, the minimum March temperature map and a map of spring maximum temperature. The Maximum Spring temperature map was created from PMIP 3 data. Reclassified Spring Max Temp Map: if map < 18 or map > 30 then the map value is 0; if map is 18-24 the map value is 100; and if the map is 25-30 then the mapvalue is 75. Best Wheat Locations Map = (Slope Map + Spring Precip Map + Min March Temp + Max Spring Temp) / 4
Slope & Rivers	Slope and Rivers Map = Slope Map and if a river is present then that location = Null()
Best Wheat & Rivers Nulled	Best Wheat and Rivers Nulled = Best Wheat Map and if a river is present then that location = Null()
Best Wheat & Rivers	Best Wheat and Rivers = Best Wheat + 25 (if a river is present)

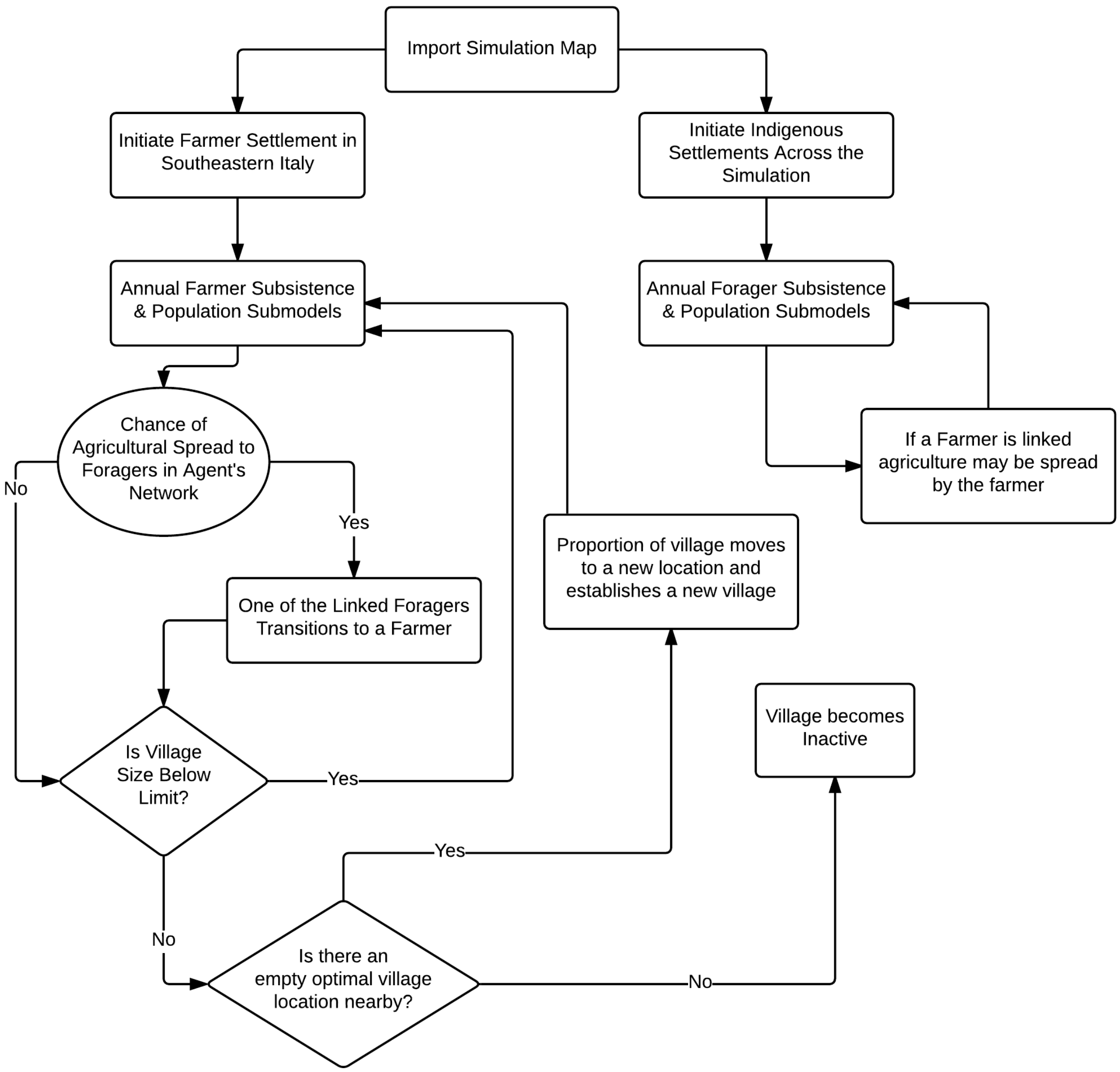
Wave of Advance Model



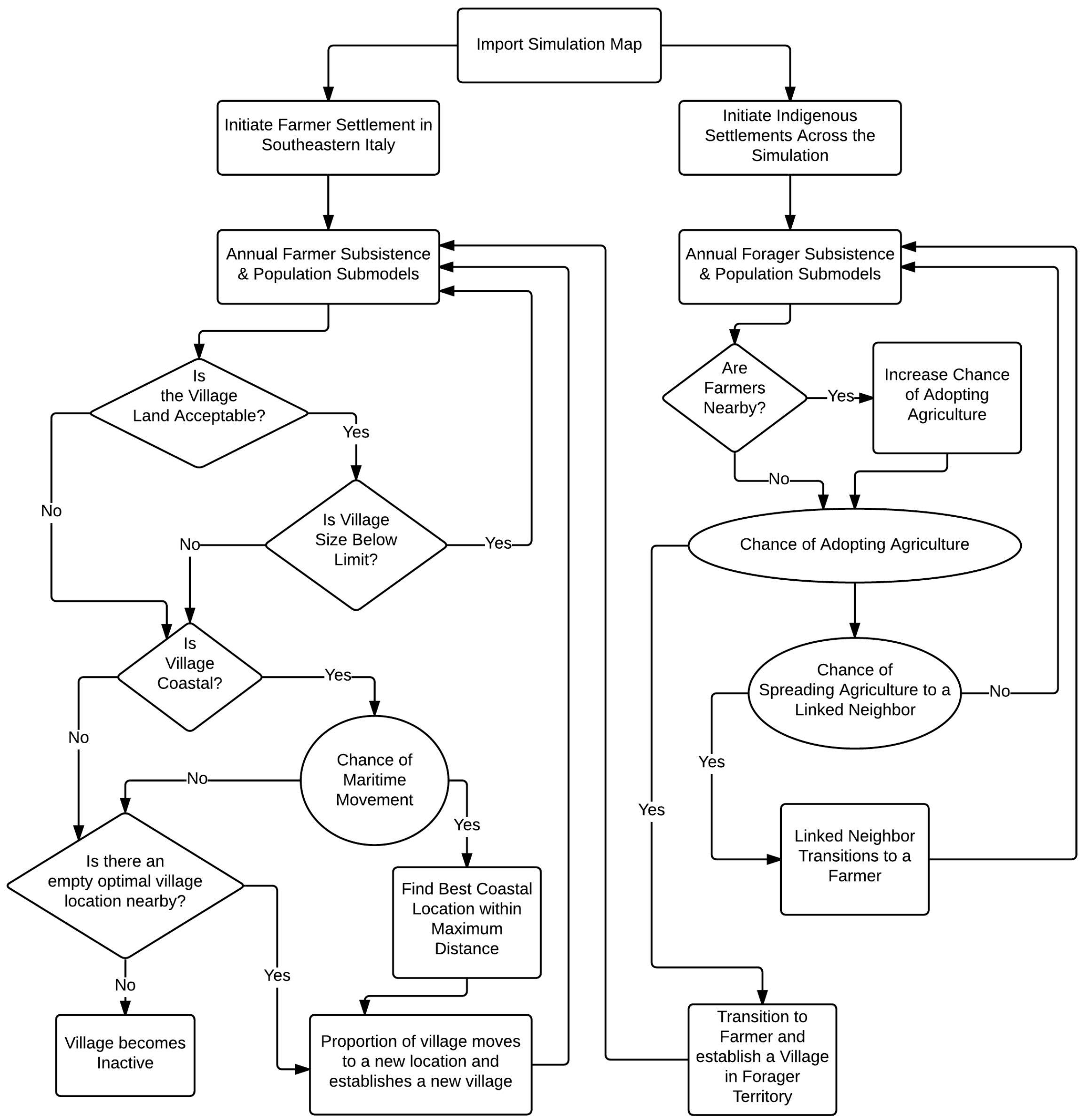
Maritime Pioneer Colonization Model



Capillary Spread Model



The Dual Model



Model Parameter	Description
spread-type	This parameter describes the type of that will occur in a model run
simulation-map	The map that a simulation will use. Agents use these maps to choose where to move
forager-strategy	The relative importance of plants and animals to forager subsistence. This effects forager density in the simulation.
farmer-strategy	The relative importance of domestic and wild resources to farmer subsistence. This effects forager density in the simulation.
forager-land	The proportion of land within the study area that is inhabited by foragers.
farmer-birth-rate	The per capita rate at which a new person is added to a village.
farmer-fissioning-proportion	The proportion of a village that fissions to form a new village
farmer-fission-subsistence-capacity	The relative proportion of the maximum carrying capacity at which a village will fission.
Forager-Neighbor-Transition-Threshold	The number of agriculturalists on neighboring patches which will trigger forager adoption of agriculture.
dual-model-farmer-gather-interaction-radius	The distance (km) within which foragers and farmers may come into contact.
capillary-spread-frequency	The annual % chance that agriculture may spread to a forager group.
network-model	Spcific rules which govern how networks are formed within the simulation
maritime-movement-frequency	Annual % chance that a fissioning village will spread via maritime expansion
coastal-leap-distance	The maximum distance (km) within which farmers may spread to coastal patches with the Maritime spread
forager-link-distance	The maximum distance (km) within which farmers may form social network links with one another
leap-distance	The maximum distance (km) that farmers can move by land.