Designing Water Efficient Residential Landscapes with Agent-Based Modeling

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Introduction
Residential irrigation accounts for 40 to 70 percent of household water use in semi-arid and arid regions in the U.S. (Hilaire et al. 2008), which consumes valuable resources. However, landscaping can also produce benefits: trees can reduce the heat index around the home, which decreases air conditioning use and saves energy (Bernatzky 1982; Shashua-Bar, Pearlmutter, and Erell 2009). The focus of my research is an agent-based system for optimizing spatial arrangements of plants on a landscape to maximize their growth and minimize their water use. The optimization criteria include a natural phenomenon known as facilitation (Callaway 1995), which is observed in water-scarce environments when larger shrubs serve as benefactors to smaller annuals by generating conditions that protect them from harsh afternoon sun (Holzapfel et al. 2006). These shrubs, known as nurse plants, enable the annuals to survive on less water than they need in the full sun (Whiting, Roll, and Vickerman 2007).

In my modeling and optimization system, called AgentScapes, each plant is an agent with growth requirements. A plant agent’s fitness at a given location is defined by a fitness function that includes those growth requirements and a penalty term designed to force facilitation. The landscape design is formulated as a combinatorial optimization problem with a discrete set of locations for each plant on a grid, a fixed number of plants, and a fitness function that defines the performance of a plant at a location. The objective is to select the best $k$ locations from $n$ possibilities, where $k$ is the number of plants and $n$ is the number of cells on the landscape. AgentScapes employs a new agent-based search algorithm designed to mimic how plant communities evolve over time in response to environmental conditions. In this algorithm, each agent acts independently to optimize its own position on the landscape through a series of local moves and random jumps.

Progress to date
The progress to date on this research includes designing the agent-based search routine, the plant growth model, and the fitness function that measures plant agent performance under different light and water conditions, and performing numerical experiments to evaluate the agent-based search routine against other optimization strategies. These experiments compared the fitness scores, the presence of facilitation and the resultant effect on water use, and spatial characteristics in the final solutions from different strategies. Details on the plant growth model, fitness function, and agent-based search were published (Hoenigman, Bradley, and Barger 2010); a summary is provided here.

Plant agent growth and fitness
Plants need light, water, and nutrients to grow. As plants grow, they influence their surroundings in numerous ways, including removing water from the soil and generating shade. The preliminary plant growth model used here includes these basic features except nutrients. This growth model is based on empirical data for how real plants respond to different levels of light and water availability (Harvey 1979). Growth increases with increasing light, up to a certain point, known as the light saturation point (Crawley 1997). Growth can also be limited by the amount of water available if the plant does not have sufficient water to support its growth rate at its light level.

Plant agents mimic this biology. The light and water requirements for plant agents are divided into discrete categories, similar to the categories for real nursery plants, and agents respond to light and water available based on these categories. The landscape conditions affecting plant growth are represented using a discrete grid, where each cell in the grid has three parameters: morning light, afternoon light, and water, representing the amount of that resource present in the cell at a given time. This formulation can capture the negative (competition) and positive (facilitation) interactions observed between heterogeneous plant types. The light is divided into morning and afternoon light to simulate the different growing conditions that can exist at different times of the day and capture the effects of facilitation in afternoon sun. Plant agents interact with the landscape by removing water from their own and surrounding cells and by generating shade.

The fitness function aims to model the fact that optimal light and water conditions for a plant agent are near the agent’s light saturation point with at least enough water available to support the agent’s growth. The fitness score
includes a biological portion based on the plant agent’s biological properties and an engineering portion—a penalty for high-water-use conditions. The plant growth model and the landscape conditions determine the biological portion of the score. The penalty is a function of the landscape light, the agent’s light saturation point, and the agent’s size. The final fitness score is based on simulating growth for multiple days to capture how the landscape changes over time. For each simulated day, the morning fitness score is calculated from the light and water available and the agent’s light and water requirements. Next, the landscape is updated by removing the water from the landscape that the agent used in the morning. This process is repeated to calculate afternoon fitness, and, again, update the landscape. The agent’s daily fitness score is the sum of its morning and afternoon fitness scores. The penalty value for light conditions beyond the plant agent’s light saturation point is then subtracted from this daily fitness score. The fitness calculation is repeated for a pre-determined number of days to get the final fitness score for a plant at a particular location. The fitness score for an arrangement of plant agents is the sum of the fitness scores for each individual agent.

Numerical experiments

Numerical experiments compared fitness scores, the presence of facilitation and water use, and spatial characteristics on simulated landscapes using different optimization strategies, including the agent-based search algorithm. The other strategies represented a range of approaches. A random algorithm—place plants randomly on the landscape—was effectively no optimization. Greedy search reflects how a gardener might design a landscape—select the best place for the plant without complete knowledge of the interactions between plants or the benefits of facilitation. Simulated annealing (SA) is a commonly used meta-heuristic with global control over the fitness function. The agent-based search is a distributed approach where each agent has a fixed number of times it can move and a local search radius. The agent searches locally and with random jumps to optimize its own location without central control.

On a series of small problems, the agent-based search algorithm produced higher fitness scores than random placements and greedy search and was competitive with SA. The agent-based search and SA were used on a series of larger problems to evaluate the presence of facilitation and the spatial characteristics of the landscapes. Both algorithms generated solutions where facilitation was common. Water use in these solutions was lower than water use in random solutions where facilitation was not common by as much as 40 percent for high-water plants. There were also notable differences in the spatial characteristics in the solutions from the agent-based search and SA algorithms. They produced different clustering patterns for the plants in ways that affected the light and water distribution on the landscape. The differences in these patterns demonstrate the value of different optimization strategies for this problem, as well as the flexibility of the agent-based model.

Research plan

The results in this research to date show that this agent-based model successfully forces facilitation, produces fitness scores competitive with other search algorithms, and generates spatial patterns that are characteristically different from those produced through another optimization strategy. The work remaining on this thesis can be summarized as follows:

- **Evaluate model parameters**—There are several model parameters that affect resource use and interactions on the landscape. These will be evaluated to determine how resource constraints generate facilitation or competition for different plant populations.

- **Fitness function modifications**—The fitness function is engineered to force facilitation. Other modifications to this function will be explored to engineer other agent behaviors that could also generate water savings. One example is clustering plants by their water requirements to reduce the variability of water requirements within a local area.

- **Evaluate other optimization strategies**—Other optimization strategies, such as genetic algorithms or scatter search, could produce different spatial patterns and will provide additional comparisons for the agent-based search.

References


