Article

Siplab, a spatial individual-based plant modelling system

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Abstract

Spatially-explicit individual-based models are important tools in forestry and plant ecology. They are commonly implemented through custom computer coding that is time-consuming, may cause compatibility and availability problems, and makes difficult the evaluation, comparison and re-use of model components. *Siplab* is an *R* package that aims at improving this situation with a flexible computing environment that can handle a variety of model forms, and without requiring advanced programming knowledge. The article briefly reviews spatial individual-plant models, and then explains the general framework used by *siplab* to represent such models in a unified way. The structure and practical use of the package are introduced through some of the examples previously discussed.

Keywords competition; growth; forestry; plant ecology; simulation; *R*; individual-tree models.

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1 Introduction

Spatially-explicit individual-based models are widely used to investigate the development of plant communities. In forestry they can be traced back to Reventlow (1960), who used them to produce yield tables around the year 1800. Staebler (1951) introduced the idea of competition indices based on overlapping zones of influence (ZOI), employed in much of the later work. Commonly known as distance-dependent individual-tree models they proliferated once electronic computers became widely available, starting with Newnham and Smith (1964). For operational growth and yield forecasting, since the 1980's these were largely replaced by simpler distance-independent (aspatial) models, but remain important research tools (Weiskittel et al., 2011; Burkhart and Tomé, 2012). In general plant ecology the interest in spatial individual-based models is more recent (Grimm, 1999), but they have received much attention (Grimm and Railsback, 2005).

Computer implementations are usually specific to each model, and often poorly documented or not publicly available. Therefore, it can be difficult to apply the models to new data and conditions, and to evaluate or combine different ideas. *Siplab* (for Spatial Individual-Plant Modelling Laboratory) is a software package intended to lessen these problems by facilitating the implementation and exploration of a wide variety of models. In what follows I describe briefly different types of spatial individual-based plant models (SIPMs), discuss their representation in *siplab*, and explain the software usage. García (2014a) includes a more technical and extensive presentation. *Siplab* uses the *R* statistical computing system (*R* Development Core Team, 2009), and is freely available from the The Comprehensive *R* Archive Network (CRAN, http://cran.r-project.org/web/packages).

2 Spatial Individual-plant Models

SIPMs predict individual growth and mortality rates as functions of the plant size, and of an index that encapsulates the effect of competing neighbors. The index may represent the results of the capture of resources by the plant (light, moisture, nutrients), which we call an assimilation index. Alternatively, one can use a competition index, related to the difference in resource capture with and without neighbors. A third approach predicts growth as the product of a potential free-growing value and a modifier that reduces the potential depending on competition. The modifier can always be written as an assimilation index divided by the free-growing potential assimilation, so that the three formulations are essentially equivalent (García, 2014a).

Many models simplify computation by considering interactions only for pairs of plants. That is, only (scalar) distances between the subject and its neighbors are used, ignoring azimuth and higher-order interactions. In contrast, other models are "fully spatial", depending on the detailed configuration of neighbor locations.

2.1 Pairwise interactions

An example is the model of Staebler (1951). Each tree has a circular zone of influence (ZOI), with a radius proportional to the tree diameter at breast height (*dbh*, Fig. 1). It is assumed that trees whose ZOIs overlap are competitors. The competition suffered by a tree should depend in some way on the extent of the ZOI intersections. Staebler ignored overlaps of 3 or more ZOIs, considering only the ZOI intersections between the subject tree and each of the neighbors taken one at a time. In addition, he avoided the complex intersection area formula by using simply the radial overlap width; the competition index is the sum of these widths.

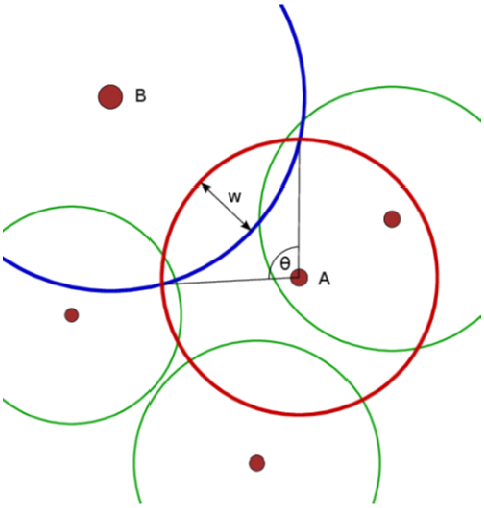

Fig. 1 Zones of influence (ZOI) and examples of pairwise competition indices. The index of Staebler (1951) is the sum of the ZOI overlap widths w, here shown for the subject tree A and competitor B. The index of Newnham and Smith (1964) uses instead the angles θ.

The model of Newnham and Smith (1964) is basically the same, but instead of the radial overlap width they used the angle subtended by the intersection (Fig. 1). Their competition index is the sum of the angles. Note that both the overlap width and the angle are functions of the sizes and distance for a pair of trees.

Hegyi (1974) defined as neighbors all trees within a given distance from the subject, and used a simple function of sizes and distance to calculate a competition index

$$\sum_j \frac{d_j / d_i}{r_{ij}} . \tag{1}$$

The sum is over the neighbors of the subject tree *i*, *d* is dbh, and r_{ij} is the distance between trees *i* and *j* (originally Hegyi added 1 foot to r_{ij} but this offset is usually ignored). Many other neighborhood rules and functions of sizes and distance have been proposed (Burkhart and Tomé, 2012).

2.2 Fully spatial

Wyszomirski (1983) developed a ZOI overlap model where intersections are shared equally among trees. This requires more information on the spatial configuration, not just sizes and distances; three-way and possibly higher-order interactions become relevant.

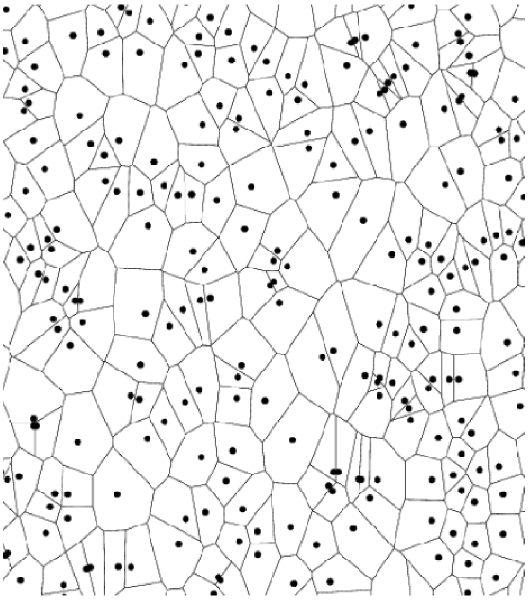

Fig. 2 Brown (1965) assessed competition through the area of the Voronoi polygons in a Dirichlet tessellation. The space or resources available at each point are allocated to the nearest tree.

Another example is the area potentially available (APA) model of Brown (1965), which partitions the plane allocating points to the closest tree (Figure 2). A tree growth rate and death probability depends on the area of its polygon, which relates to the amount of available resources captured by that tree and acts as an assimilation index. A number of variations on this idea where the partitioning depends on tree size have been used (Burkhart and Tomé, 2012).

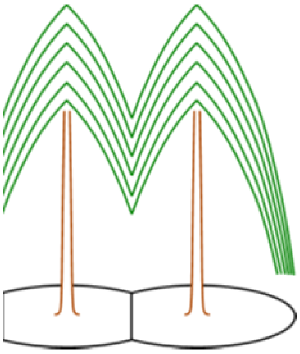

Fig. 3 Crowns in the TASS model move upward with height growth, preserving their shape and maintaining a number of annual foliage layers. Contact with neighbors generates a tessellation of the plane (possibly including unallocated areas). After Mitchell (1975, page 7).

The TASS model of Mitchell (1975) is based on 3-dimensional crown interactions. It is assumed that radial crown growth is a function of distance from the top, ceasing when the tree branches become in contact with those of the neighbors (Fig. 3). A certain number of annual foliage layers that receive sufficient light survive. The result is that the green crown is a hollow shell of constant shape but variable horizontal extent that moves upward with height growth, possibly over-topping smaller trees that eventually die. Stem volume increment depends on the amount of foliage. It is seen that this is essentially determined by an induced partitioning of horizontal space, except for some tapering of the foliage depth near free crown edges. Relationships between 3-D crown intersections and 2-D projection partitioning were analyzed by Gates et al. (1979).

Wu et al. (1985) proposed an "ecological field theory", where plants have a competitive potential represented on the plane by a function that depends on plant size and decreases exponentially with distance from the plant location. Instead of an all-or-none allocation, resources at each point are shared according to the plant potentials. The model of Berger and Hildenbrandt (2000) is similar, but the potential is truncated at 0 beyond a certain distance.

3 The *Siplab* Approach

Siplab calculates competition or assimilation indices specified in ways that include and extend ideas from the examples above.

Describing pairwise interaction models is simple; first one specifies a neighborhood rule for choosing potential competitors. Then, one gives a function of sizes and distance for a pair of neighbors, called a competition kernel. The competition kernel value is summed over the neighbors of a subject plant to obtain its competition index. Actually, a separate neighborhood rule is optional, it just identifies pairs for which the competition kernel is 0, but it can be useful for clarity and to save some computation.

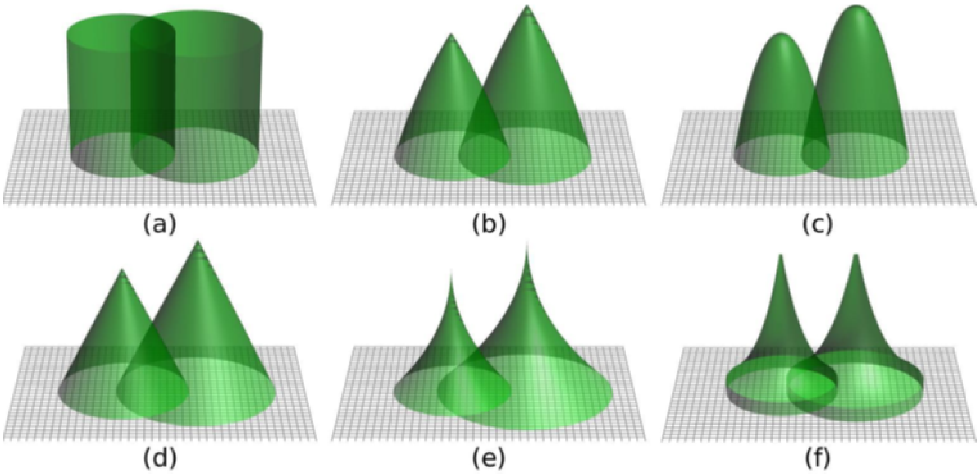

Fig. 4 Examples of influence functions. (a) ZOI intersections as in Wyszomirski (1983). (b) TASS. (c)-(e) Power functions based on Gates et al. (1979). (f) Berger and Hildenbrandt (2000). From García (2014a).

Fully spatial models are somewhat more complex, the specification involves 4 stages:

Resources. *Siplab* discretizes an area into small pixels that contain "resources", e. g., light, moisture, nutrients. The default uniform spatial distribution is used by most models, but any other resource distribution could be given to study the effect of spatial correlations, gradients, etc.

Influence function. The competitive potential of a plant is described by a given influence function, typically dependent on the plant size and decreasing with distance (Fig. 4). Examples include cylinders for ZOI overlap models, the crown surface of TASS, the power functions of Gates et al. (1979), and the field potentials of Wu et al. (1985) and Berger and Hildenbrandt (2000). Brown's APA is generated by an influence function in the shape of a paraboloid of revolution (Gates et al., 1979; García, 2014a). Some of these are provided with the package, and it is easy to program others as *R* functions. A vector distance is passed as an argument, so the functions could be asymmetric for simulating directional light radiation or for other purposes.

Allotment. In APA and in TASS, at any point (or pixel) the plant with the largest influence takes all the resource; competition at the point is completely asymmetric or one-sided. In contrast, in ecological field theory and similar models the resource is shared among plants depending on their influence function values. *Siplab* covers a range of possibilities by allotting to plant *i* a proportion of the pixel's resources equal to

$$\frac{\varphi_i^\alpha}{\sum \varphi_j^\alpha}\ , \tag{2}$$

where φ are influence function values, α is an asymmetry parameter, and the sum is over all the plants with positive influence at that point. An $\alpha = 0$ corresponds to complete symmetry, with equal allotment independently of size (Wyszomirski, 1983), $\alpha = 1$ allocates the resource in direct proportion to the influence values, and the limit $\alpha \to \infty$ gives the one-sided allotment.

Efficiency. For each plant, the allotted resource is summed over all the pixels to compute the plant assimilation index. Alternatively, the sum can be weighted by a user-supplied efficiency function, reflecting a distance-dependent resource contribution or utilization cost. It might make sense to use an efficiency function of the same form as the influence function, scaled to be 1 at the plant location, and some of these are provided.

In mixed-species stands, influence and efficiency function parameters can be species-dependent.

4 Implementation and Usage

Siplab is written in *R*, on top of the *spatstat* spatial statistical analysis package (Baddeley and Turner, 2005). It takes advantage of efficient data structures and algorithms already available in *spatstat*, simplifying the additional coding and documentation needed for the plant modelling computations. This strategy facilitates also data preparation and the analysis of simulation output, which can make use of tools available in *spatstat* and other *R* components.

4.1 Pairwise

Competition indices for pairwise interaction models are obtained with the pairwise function. It makes use of the *spatstat* function `applynbd` that for any individual returns a list of neighbors satisfying certain conditions, resulting in a straightforward implementation. An example is computing Hegyi's index:

```
result <- pairwise(trees, maxR = 6, kernel = powers.ker,
    kerpar = list(pi=1, pj=1, pr=1, smark="diameter")))
```

Here `trees` is a *spatstat* object of class `ppp` containing the tree coordinates and attributes (marks), `maxR = 6` specifies a 6 m circular neighborhood, and `powers.ker` is a built-in competition kernel function

$$\frac{d_j^{p_j}/d_i^{p_i}}{r_{ij}^{p_r}}, \tag{3}$$

a generalization of eq. (1) that includes many of the competition indices in the literature. The `kerpar` list contains parameters passed on to the competition kernel function, in this instance the kernel exponents and an identifier for the size variable. The result is the `trees` object with an additional variable containing the competition indices.

The general form of a call to `pairwise` is

```
pairwise(plants, maxN, maxR, select, selpar, kernel, kerpar)
```

Default argument values are `NULL`, except for `plants` and `kernel` that are required. Besides the arguments in the example above, `maxN` specifies a maximum number of trees in the neighborhood, and `select`, with parameters in `selpar`, is an optional logical function defining more general neighborhood rules.

Several common forms of `kernel` and `select` are included in the package. Others can be programmed, most easily by editing one of the available functions.

4.2 Fully spatial

The function `assimilation` calculates assimilation indices for fully spatial models. Optionally, it also computes free-growing assimilations, so that competition indices or potential/modifier forms can be obtained. As an example, the following call gives assimilation indices based on the TASS model of Mitchell (1975):

```
result <- assimilation(trees, influence = tass.inf,
    infpar = list(b=3.432, c=6.1, smark=1), asym = Inf)
```

The `ppp` object `trees` contains the tree coordinates in meters, and the heights as the first or only mark. It uses the built-in influence function `tass.inf` with the parameters in `infpar`, one-sided allotment (asymmetry index $\alpha \to \infty$), and there is no efficiency weighting. The assimilation indices are returned as an additional mark named `aindex`.

The general form, showing default argument values, is:

```
assimilation(plants, pixsize = 0.2, resource = 1,
    influence = gnomon.inf, infpar = list(a=1, b=4, smark=1),
    asym = Inf, efficiency = flat.eff, effpar = NULL,
```

```
        plot = TRUE, afree = FALSE, centroid = FALSE)
```

Additional arguments are the pixel size `pixsize`, an array or function `resource` with the resource spatial distribution (defaulting to uniform), an efficiency function `efficiency` with parameters in `effpar`, and flags for the optional output of graphics, free-growing assimilation, and centroid of the effective assimilation for each plant. The centroids were used in García (2014b), where the *Supplementary Files* contain examples of advanced *siplab* use.

Assimilation or competition indices near the edges of the sample are distorted because competitors are missing. Functions `edges` and `core` are available to correct for edge effects by omitting border trees or by plot replication.

Full usage details are available in the *Reference Manual* at http://cran.r-project.org/web /packages/siplab/siplab.pdf.

5 Conclusions

Siplab calculates competition or assimilation indices specified in ways that include and extend many of those described in the literature. It is possible to emulate published models, generalize them, and to "mix and match" components from different models. This is done within a flexible and convenient computational environment that does not require major programming skills. It is expected that this and similar approaches may improve transparency and reproducibility in forest modelling, and allow for the evaluation and comparison of alternative formulations on an equal footing.

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