



R Marries NetLogo: Introduction to the RNetLogo Package

Jan C. Thiele

University of Göttingen

Abstract

The **RNetLogo** package delivers an interface to embed the agent-based modeling platform NetLogo into the R environment with headless (no graphical user interface) or interactive GUI mode. It provides functions to load models, execute commands, push values, and to get values from NetLogo reporters. Such a seamless integration of a widely used agent-based modeling platform with a well-known statistical computing and graphics environment opens up various possibilities. For example, it enables the modeler to design simulation experiments, store simulation results, and analyze simulation output in a more systematic way. It can therefore help close the gaps in agent-based modeling regarding standards of description and analysis. After a short overview of the agent-based modeling approach and the software used here, the paper delivers a step-by-step introduction to the usage of the **RNetLogo** package by examples.

Keywords: NetLogo, R, agent-based modeling, ABM, individual-based modeling, IBM, statistics, graphics.

1. Introduction

1.1. Agent- and individual-based modeling

Agent-based models (ABMs) or individual-based models (IBMs), as they are called in ecology and biology, are simulation models that explicitly represent individual agents, which can be, for example, humans, institutions, or organisms with their traits and behavior (Grimm and Railsback 2005; Gilbert 2008; Thiele, Kurth, and Grimm 2011). A key characteristic of this modeling approach is that simulation results emerge from the more or less complex interactions among the agents. Therefore, such models are useful when local interactions on the micro level are essential for the description of patterns on the macro level.

The origins of the ABM approach go back to the late 1970s (e.g., [Hewitt 1976](#)) with the development of so-called multi-agent systems (MASs) in computer science as a part of the distributed artificial intelligence (DAI) research area ([Green, Hurst, Nangle, Cunningham, Somers, and Evans 1997](#); [Sycara 1998](#)). Their wider use in computer science began only in the 1990s ([Luck, McBurney, and Preist 2003](#); [Wooldridge 2002](#); [Weiss 1999](#)). Definitions of the term MAS and what an agent is, can be found for example in [Wooldridge \(2002\)](#) and [Jennings \(2000\)](#). Examples for the use of MASs with intelligent agents in the field of computer science include computer games, computer networks, robotics for manufacturing, and traffic-control systems (for examples, see [Oliveira 1999](#); [Luck *et al.* 2003](#); [Shen, Hao, Yoon, and Norrie 2006](#); [Moonen 2009](#)).

With increasing importance of questions about coordination and cooperation within MASs the connections to social sciences arose ([Conte, Gilbert, and Sichman 1998](#)) and the field of agent-based social simulation (ABSS), that is, an agent-based modeling approach as part of computational sociology became a 'counter-concept' to the classical top-down system dynamics and microsimulation approaches ([Gilbert 1999](#); [Squazzoni 2010](#)). ABSS is mainly used for theory testing and development ([Macy and Willer 2002](#); [Conte 2006](#)) and applied to simulations of differentiation, diffusion, and emergence of social order in social systems (for examples, see listings in [Macy and Willer 2002](#); [Squazzoni 2010](#)) as well as to questions about demographic behavior ([Billari and Prskawetz 2003](#)). The most famous models in social sciences are Schelling's segregation model ([Schelling 1969](#)) and the Sugarscape model of [Epstein and Axtell \(1996\)](#).

Strongly related to the development of ABMs in social sciences is the establishment of the ABM approach in economics, which is called agent-based computational economics (ACE) and related to the field of cognitive and evolutionary economics. The aims of ACE can be divided into four categories: empirical understanding, normative understanding, qualitative insight as well as theory generation and methodological advancement (for details, see [Tesfatsion 2006](#)). It was applied, for example, to the reproduction of the classical cobweb theorem (e.g., [Arifovic 1994](#)), to model financial/stock markets (see [LeBaron 2000](#), for a review) as well as to the simulation of industry and labor dynamics (e.g., [Leombruni and Richiardi 2004](#)).

In contrast to ABSS and ACE, the agent-based modeling approach has a slightly longer tradition in ecology ([Grimm and Railsback 2005](#)). The development of so-called individual-based models is less closely related to the developments of MASs, because ecologists early became aware of the restrictions in classical population models (differential equation models) and looked for alternatives. Over the last three to four decades hundreds of IBMs were developed in ecology ([DeAngelis and Mooij 2005](#)). For reviews see, for example, [Grimm \(1999\)](#) and [DeAngelis and Mooij \(2005\)](#).

Besides these four main research areas, there are many other disciplines in which ABMs are increasingly used, often within an interdisciplinary context. Examples include ecological economics (e.g., [Heckbert, Baynes, and Reeson 2010](#)), marketing/socio-psychology (e.g., [North *et al.* 2010](#)), archaeology/anthropology (e.g., [Griffin and Stanish 2007](#)), microbiology (e.g., [Ferrer, Prats, and López 2008](#)), biomedicine/epidemiology (e.g., [Carpenter and Sattenspiel 2009](#)), criminology (strongly related to ABSS, e.g., [Malleon, Heppenstall, and See 2010](#)) and land-use management (e.g., [Matthews, Gilbert, Roach, Polhill, and Gotts 2007](#)).

1.2. Links to statistics

Links to statistics can be found in agent-based modeling along nearly all stages of the modeling cycle. Often, models are developed on the basis of empirical/field data. This gives the first link to statistics as data are analyzed with statistical methods to derive patterns, fit regression models and so on to construct and parameterize the rules and to prepare input as well as validation data.

Often, agent-based model rules depend on statistical methods applied during a simulation run. In very easy cases, for example, animal reproduction could depend on the sum of the food intake in a certain period but it is also possible for agent behaviors to be based on correlation, regression, network, point pattern analysis etc.

The third link comes into play when the model is formulated and implemented and some parameters of the model are unknown. Then, methods of inverse modeling with different sampling schemes, Bayesian calibration, genetic algorithms and so on can be used to obtain feasible parameter values.

In the next stage, the model application, methods like uncertainty and sensitivity analysis provide important tools to gain an understanding of the systems' behavior and functioning, i.e., to open the black box of complexity.

The last link to statistics is the further analysis of the model output using descriptive as well as inferential statistics. Depending on the type of model, this can include correlation analysis, hypothesis testing, network analysis, spatial statistics, time series analysis, survival analysis etc.

The focus in this article is on those parts where statistical methods are applied in combination with the model runs.

1.3. NetLogo

Wilensky's NetLogo ([Wilensky 1999](#)) is an agent-based modeling tool developed and maintained since 1999 by the Center for Connected Learning and Computer-Based Modeling at Northwestern University, Illinois. It is an open-source software platform programmed in `Java` and `Scala` and especially designed for the development of agent-based simulation models. It comes with an integrated development and simulation environment. It provides many predefined methods (so-called primitives and reporters) for behavioral rules of the agents. Because it has a Logo-like syntax and standard agent types (turtles, patches, links), in combination with a built-in GUI, it is very easy to learn. Due to its simplicity and relatively large user community, it is becoming the standard platform for communicating and implementing ABMs that previously has been lacking.

For an introduction to NetLogo see its documentation ([Wilensky 2013](#)). An introduction into agent-based modeling using NetLogo can be found, for example, in [Railsback and Grimm \(2012\)](#) or [Wilensky and Rand \(2014\)](#).

1.4. R

R ([R Core Team 2014a](#)) is a well-known and established language and open source environment for statistical computing and graphics with many user-contributed packages.

For NetLogo users not yet familiar with R: R is very well documented; see, for example, the R

language definition (R Core Team 2014c). Furthermore, many tutorials can be found in the web, for example, Maindonald (2008); Venables, Smith, and R Core Team (2014); Kabacoff (2011); Owen (2010); and many books are available, for example, Zuur, Ieno, and Meesters (2009); Crawley (2005); Kabacoff (2010); Venables and Ripley (2002).

1.5. Note on this article

This work is a mixture of scientific article and tutorial for a scientific tool; writing styles differ between these two elements, but section headings indicate what element each section contains.

2. Introducing RNetLogo

RNetLogo (Thiele 2014) is an R package that links R and NetLogo; i.e., any NetLogo model can be run and controlled from R and simulation results can be transferred back to R for statistical analyses. This is desirable as NetLogo’s support of systematic design, performance, and analysis of simulation experiments is limited. In general, much more could be learned from ABMs if they were embedded in a rigorous framework for designing simulation experiments (Oh, Sanchez, Lucas, Wan, and Nissen 2009), storing simulation results in a systematic way, and using statistical toolboxes for analyzing these results. **RNetLogo** can be used to bridge this gap since R (together with the enormous number of packages) delivers such tools. Such a seamless integration was already the scope of the **NetLogo-Mathematica Link** (Bakshy and Wilensky 2007a), which was designed to make use of Mathematica’s functionality for “advanced import capabilities, statistical functions, data visualization, and document creation. With **NetLogo-Mathematica Link**, you can run all of these tools side-by-side with NetLogo” (Bakshy and Wilensky 2007b). **RNetLogo** offers such a framework for two freely available open source programs with fast-growing communities. **RNetLogo** itself is open-source software published under the GNU GPL license.

RNetLogo consists of two parts: R code and Java code (Figure 1). The R code is responsible for offering the R functions, for connecting to Java, and for doing data transformations, while the Java code communicates with NetLogo.

To connect the R part of **RNetLogo** to the Java part the **rJava** package for R (Urbanek 2010) is used. The **rJava** package offers the ability to create objects, call methods and access class members of Java objects through the Java Native Interface (JNI, Oracle 2013) from C. The Java part of the **RNetLogo** package connects to the Java **Controlling API** of NetLogo. This API allows controlling NetLogo from Java (and Scala) code (for details, see Tisue 2012).

When NetLogo code is given to an **RNetLogo** function, i.e., to the R part of **RNetLogo**, it is submitted through **rJava** to the Java part of **RNetLogo**, and from there to NetLogo’s **Controlling API** and thence to NetLogo. In case of reporters, i.e., primitives with return values, the return value is collected by the Java part of **RNetLogo**, transformed from Java to R by **rJava** and sent through the R part of **RNetLogo** to R.

Currently **RNetLogo** provides 17 functions (Table 1).

The functions that handle NetLogo code, like **NLCommand** or **NLReport**, expect it as a string. Some other functions, e.g., **NLGetAgentSet**, construct such strings internally from the different function arguments in the R part of **RNetLogo**. This string is then sent to the Java part of

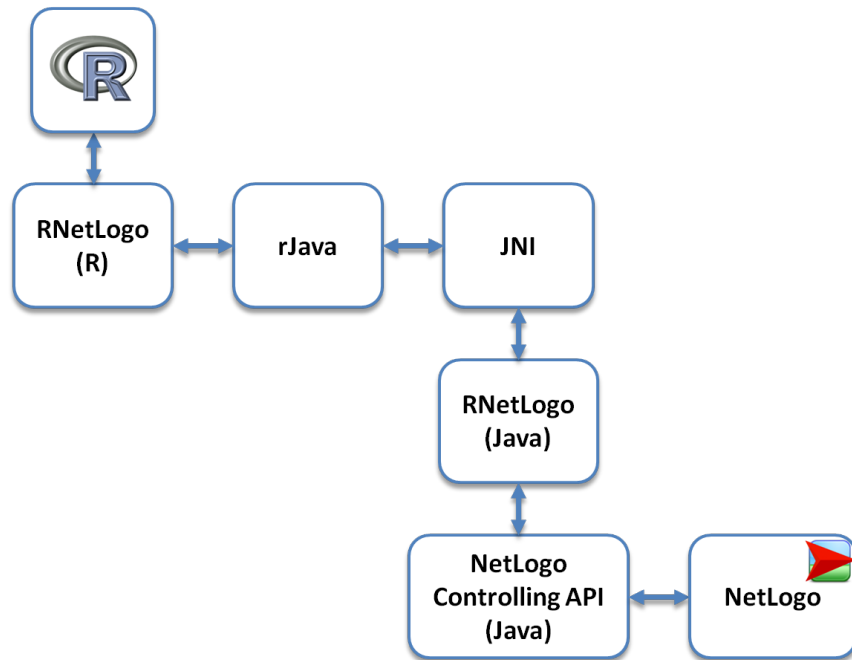


Figure 1: **RNetLogo** consists of two parts: an R and a Java part. The R part adds the **RNetLogo** functions to R and uses **rJava** to connect the Java part. The Java part connects to NetLogo via the **Controlling API** of NetLogo.

RNetLogo and from there it is evaluated through NetLogo’s **Controlling API**.

When the submitted NetLogo code is not valid NetLogo throws an exception of type ‘Logo-Exception’ or ‘CompilerException’ containing the corresponding error message. This exception is further thrown by the Java part of **RNetLogo**, handled by **rJava**, and requested finally by the R part of **RNetLogo** and printed to R’s command line. Runtime errors in NetLogo, like ‘java.lang.OutOfMemoryError’, are reported in the same manner. A message in R’s command line is printed. But errors where the JVM crashes can cause crashes in **rJava**, which can affect the R session as well.

Some functions of **RNetLogo**, like `NLDoCommand` or `NLDoReportWhile`, require further control flow handling, i.e., loops and condition checkings, which are done by the Java part of **RNetLogo**. The methods `command` and `report` of class `org.nlogo.workspace.Controllable` of NetLogo’s **Controlling API** are used as interfaces to NetLogo. All other things are done by the R and the Java part of **RNetLogo**.

2.1. What else?

If only the integration of R calculations into NetLogo (i.e., the other way around) is of interest, a look at the **R-Extension** to NetLogo at <http://r-ext.sourceforge.net/> (see also Thiele and Grimm 2010) can be useful.

If we want to use the **R-Extension** within a NetLogo model controlled by **RNetLogo**, we should use the **Rserve-Extension** instead (available at <http://rserve-ext.sourceforge.net/>), because loading the **R-Extension** will crash as it is not possible to load the JRI library when **rJava** is active.

Function	Scope	Arguments	Return value
NLStart	Creates an instance of NetLogo .	<code>nl.path</code> <code>gui</code> <code>nl.version</code> <code>is3d</code>	–
NLLoadModel	Loads a model into the NetLogo instance.	<code>model.path</code>	–
NLQuit	Quits a NetLogo instance.	<code>all</code>	–
NLCommand	Executes a command in the referenced NetLogo instance.	<code>... [strings containing NetLogo commands]</code>	–
NLDoCommand	Repeats execution of a command in the referenced NetLogo instance a defined number of times.	<code>iterations</code> <code>... [strings containing NetLogo commands]</code>	–
NLDoCommandWhile	Repeats a command in the referenced NetLogo instance while a NetLogo reporter returns TRUE .	<code>condition</code> <code>... [strings containing NetLogo commands]</code> <code>max.minutes</code>	–
NLReport	Reports a value or list of values.	<code>reporter</code>	Result of the reporter.
NLDoReport	Repeats a command and a reporter in the referenced NetLogo instance a defined number of times.	<code>iterations</code> <code>command</code> <code>reporter</code> <code>as.data.frame</code> <code>df.col.names</code>	Concatenated result of repeated reporter calls.
NLDoReportWhile	Repeats execution of a command and a reporter in the referenced NetLogo instance while a conditional reporter returns TRUE .	<code>condition</code> <code>command</code> <code>reporter</code> <code>as.data.frame</code> <code>df.col.names</code> <code>max.minutes</code>	Concatenated result of repeated reporter calls.

NLGetAgentSet	Reports variable values of one or more agents as a data frame (optionally as a list or vector).	<code>agent.var</code> <code>agentset</code> <code>as.data.frame*</code> <code>agents.by.row*</code> <code>as.vector*</code>	Values of all requested agent variables of all requested agents.
NLGetPatches	Reports the values of patch variables as a data frame (optionally as a list, matrix or simple vector).	<code>patch.var</code> <code>patchset</code> <code>as.matrix*</code> <code>as.data.frame*</code> <code>patches.by.row*</code> <code>as.vector*</code>	Values of all requested patch variables of all requested patches.
NLGetGraph	Captures a network of links.	<code>link.agentset*</code>	igraph graph object of link agents.
NLSetAgentSet	Sets a variable of one or more agents to values in a data frame or vector.	<code>agentset</code> <code>input</code> <code>var.name</code>	—
NLSetPatches	Sets a variable of all patches in the NetLogo World to the values in a matrix.	<code>patch.var</code> <code>in.matrix</code>	—
NLSetPatchSet	Sets the variable value of one or more patches to values in a data frame.	<code>input</code> <code>patch.var</code>	—
NLDfToList	Transforms a data frame into a NetLogo list or multiple NetLogo lists (one for each column of the data frame).	<code>in.data.frame</code>	—
NLSourceFromString	Appends a string to the NetLogo model's code.	<code>... [strings containing model source code]</code> <code>append.model*</code>	—

Table 1: Functions provided by **RNetLogo**. All functions take an additional (optional) argument `nl.obj` which is not listed in the table. It is a string identifying a NetLogo instance created with `MLStart`. Where functions take wildcard arguments (`...`) a short description is given in squared brackets. Optional arguments are marked with an asterisk. Details to the functions can be found in the manual pages of **RNetLogo**.

3. Using RNetLogo – Hands-on

3.1. Installation

To install and use **RNetLogo** we must have R (available from the Comprehensive R Archive Network at <http://CRAN.R-project.org/>) and NetLogo (<http://ccl.northwestern.edu/netlogo/download.shtml>) installed. The **RNetLogo** package is available from CRAN (<http://CRAN.R-project.org/package=RNetLogo/>) and is installed like any other R package; see chapter 6 of R's installation and administration manual (R Core Team 2014b) for information on how to install a package. However, **RNetLogo** requires the **rJava** package (Urbanek 2010), available from CRAN. It can happen that we have to reconfigure Java/R after installing **rJava** on Unix machines. This topic has been discussed several times; see, for example, RWiki (2006). The following sections provide an introduction to the usage of **RNetLogo**, however, there are some pitfalls described in Section 5 one should be aware before starting own projects.

3.2. Loading NetLogo

To use the **RNetLogo** package the first time in an R session we have to load the package, like any other packages, with

```
R> library("RNetLogo")
```

When loading **RNetLogo** it will automatically try to load **rJava**. If this runs without any error we are ready to start NetLogo (if not, see Section 3.1). To do so, we have to know where NetLogo is installed. What we need is the path to the folder that contains the NetLogo.jar file. On Windows machines this could be C:/Program Files/NetLogo 5.0.5/. Here, we assume that the R working directory (see, e.g., functions `setwd()`) is set to the path where NetLogo is installed.

Now, we have to decide whether we want to run NetLogo in the background without seeing the graphical user interface (GUI) and control NetLogo completely from R or if we want to see and use the NetLogo GUI. In the latter case, we can use NetLogo as it was started independently, i.e., can load models, change the source code, click on buttons, see the NetLogo View, inspect agents, and so on, but also have control over NetLogo from R. The disadvantage of starting NetLogo with GUI is that we cannot run multiple instances of NetLogo in one R session. This is only possible in the so called headless mode, i.e., running NetLogo without GUI (see Section 3.6 for details). Linux and Mac users should read the details section of the `NLStart` manual page (by typing `help(NLStart)`).

Due to NetLogo's **Controlling API** changes with the NetLogo version, we have to use an extra parameter `n1.version` to start **RNetLogo** for NetLogo version 4 (`n1.version = 4` for NetLogo 4.1.x, `n1.version = 40` for NetLogo 4.0.x). The default value of `n1.version` is 5, which means that we do not have to submit this parameter when using NetLogo 5.0.x. Since NetLogo 5.0.x operates much faster on lists than older versions it is highly recommended to use it here (see also the **RNetLogo** package vignette "Performance Notes and Tests").

To keep it simple and comprehensible we start NetLogo with GUI by typing:

```
R> n1.path <- getwd()
R> NLStart(n1.path)
```

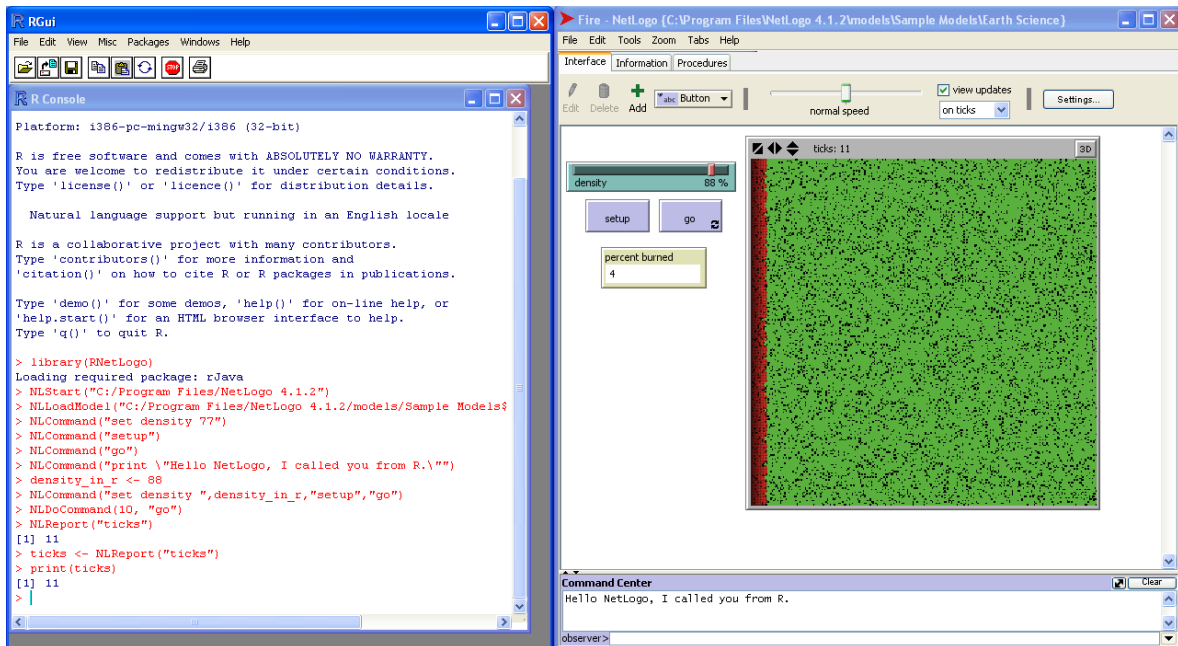



Figure 2: NetLogo (on the right) started and controlled from R (on the left).

If everything goes right, a NetLogo Window will be opened. We can use the NetLogo window as if it had been started independently, with the exception that we cannot close the window through clicking. On Windows, NetLogo appears in the same program group at the taskbar as R. If possible, arrange the R and NetLogo windows so that we have them side by side (Figure 2), and can see what is happening in NetLogo when we submit the following code.

3.3. Loading a model

We can now open a NetLogo model by just clicking on "File -> Open..." or choosing one of the sample models by clicking on "File -> Models Library". But to learn to control NetLogo from R as when starting NetLogo in headless mode, we type in R:

```
R> model.path <- file.path("models", "Sample Models", "Earth Science",
+   "Fire.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
```

The Forest Fire model (Wilensky 1997a) should be loaded. This model simulates a fire spreading through a forest. The expansion of the fire depends on the density of the forest. The forest is defined as a tree density value of the patches, while the fire is represented by turtles. If we want, we can now change the initial tree density by using the slider on the interface tab and run the simulation by clicking on the setup button first and then on the go button. In the next section, we will do the same by controlling NetLogo from R.

3.4. Principles of controlling a model

In a first step, we will change the density value, i.e., the position of the density slider, by submitting the following statement in R:

```
R> NLCommand("set density 77")
```

The slider goes immediately to the position of 77 percent. We can now execute the `setup` procedure to initialize the simulation. We just submit in R:

```
R> NLCommand("setup")
```

And again, the command is executed immediately. The tick counter is reset to 0, the View is green and first fire turtles are found on the left side of the View. Please notice that the `NLCommand` function does not press the setup button, but calls the `setup` procedure. In the Forest Fire example it makes no difference as the setup button also just calls the `setup` procedure, but it is possible to add more code to a button than just calling a procedure. But we can copy and paste such code into the `NLCommand` function as well.

We now want to run one tick by executing the `go` procedure. This is nothing new; we just submit in R:

```
R> NLCommand("go")
```

We see that the tick counter was incremented by one and the red line of the fire turtles on the left of the View extended to the next patch.

As we have seen, the `NLCommand` function can be used to execute any command which could be typed into NetLogo's command center. We can, for example, print a message into NetLogo's command center with the following statement:

```
R> NLCommand("print \"Hello NetLogo, I called you from R.\")")
```

The backslashes in front of the quotation marks are used to “mask” the quotation marks; otherwise R would think that the command string ends after the `print` and would be confused. Furthermore, it is possible to submit more than one command at once and in combination with R variables. We can change the density slider and execute `setup` and `go` with one `NLCommand` call like this:

```
R> density.in.r <- 88
R> NLCommand("set density ", density.in.r, "setup", "go")
```

In most cases, we do not want to execute a `go` procedure only a single time but for, say, ten times (ticks). With the **RNetLogo** package we can do this with:

```
R> NLDoCommand(10, "go")
```

Now we have run the simulation for eleven ticks and maybe want to have this information in R. Therefore, we execute:

```
R> NLReport("ticks")
```

```
[1] 11
```

As you might expect, we can save this value in an R variable by typing:

```
R> ticks <- NLReport("ticks")
R> print(ticks)
```

[1] 11

This was already the basic functionality of the **RNetLogo** package. In the following section we mostly modify and/or extend this basic functionality.

NetLogo users should note that there is no "forever button". To run a simulation for several ticks we can use one of the loop functions (`NLDoCommand`, `NLDoCommandWhile`, `NLDoReport`, `NLDoReportWhile`) or write a custom procedure in **NetLogo** that runs the `go` procedure the desired number of times when called once by R.

To quit a **NetLogo** session, i.e., to close a **NetLogo** instance, we have to use the `NLQuit` function. If we used the standard GUI mode without assigning the **NetLogo** instance to an R variable, we can write:

```
R> NLQuit()
```

Otherwise, we have to specify which **NetLogo** instance we want to close by specifying the R variable storing it. Please note that there is currently no way to close the GUI mode completely. That is why we cannot run `NLStart` again in the same R session when **NetLogo** was started with its GUI.

3.5. Advanced controlling functions

In Section 3.4, we used the `NLDoCommand` function to run the simulation for ten ticks. Here, we will run the model for ten ticks as well, but we will collect the percentage of burned trees after every tick automatically:

```
R> NLCommand("setup")
R> burned <- NLDoReport(10, "go", "(burned-trees / initial-trees) * 100")
R> print(unlist(burned))
```

```
[1] 0.4192073 0.7821574 1.1287747 1.4790215 1.8238240 2.1649971
[7] 2.5116144 2.8836382 3.2629210 3.6349448
```

This code ran the simulation for ten ticks and wrote the result of the given reporter (the result of the calculation of the percentage of burned trees) after every tick into the R list `burned`.

If we want to run the simulation until no trees are left and know the percentage of burned trees in every tick, we can execute:

```
R> NLCommand("setup")
R> burned <- NLDoReportWhile("any? turtles", "go",
+   c("ticks", "(burned-trees / initial-trees) * 100"),
+   as.data.frame = TRUE, df.col.names = c("tick", "percent burned"))
R> plot(burned, type = "s")
```

The first argument of the function takes a **NetLogo** reporter. Here, the `go` procedure will be executed while there are turtles in the simulation, i.e., `any? turtles` reports `true`. Moreover, we have used not just one reporter (third argument) but a vector of two reporters; one returning the current simulation time (`tick`) and a second with the percentage of burned

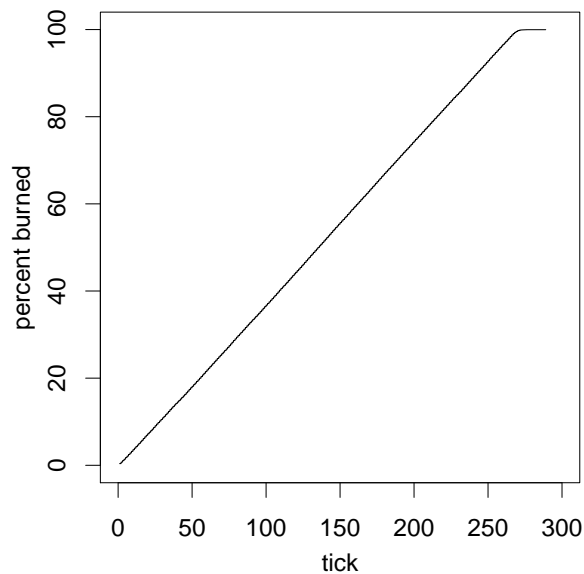


Figure 3: The percentage of burned trees over time as the result of `NLDoReportWhile`, which runs as long as there are turtles (`any? turtles`).

trees. Furthermore, we have defined that our output should be saved as a data frame instead of a list and we have given the names of the columns of the data frame by using a vector of strings in correspondence with the reporters. At the end, the R variable `burned` is of type `data.frame` and contains two columns; one with the `tick` number and a second with the corresponding percentage of burned trees. By using the standard plot function, we graph the percentage of burned trees over time (Figure 3).

To demonstrate the `NLGetAgentSet` function, we use a different model. Therefore, we load the Tumor model from NetLogo's Models Library, set it up and run it for 20 ticks, as follows:

```
R> model.path <- file.path("models", "Sample Models", "Biology",
+   "Tumor.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
R> NLCommand("setup")
R> NLDoCommand(20, "go")
```

After we have run 20 ticks, we load the x and y positions of all tumor cells (which are turtles) into a data frame and show them in a plot. But before we call the plot function, we will get the spatial extent of the NetLogo World to use in the plot window (Figure 4):

```
R> cells <- NLGetAgentSet(c("xcor", "ycor"), "turtles")
R> x.minmax <- NLReport("(list min-pxcor max-pxcor)")
R> y.minmax <- NLReport("(list min-pycor max-pycor)")
R> plot(cells, xlim = x.minmax, ylim = y.minmax, xlab = "x", ylab = "y")
```

In a second step, we get only the metastatic cells and plot them again (Figure 5):

```
R> cells.metastatic <- NLGetAgentSet(c("xcor", "ycor"),
+   "turtles with [metastatic? = True]")
```

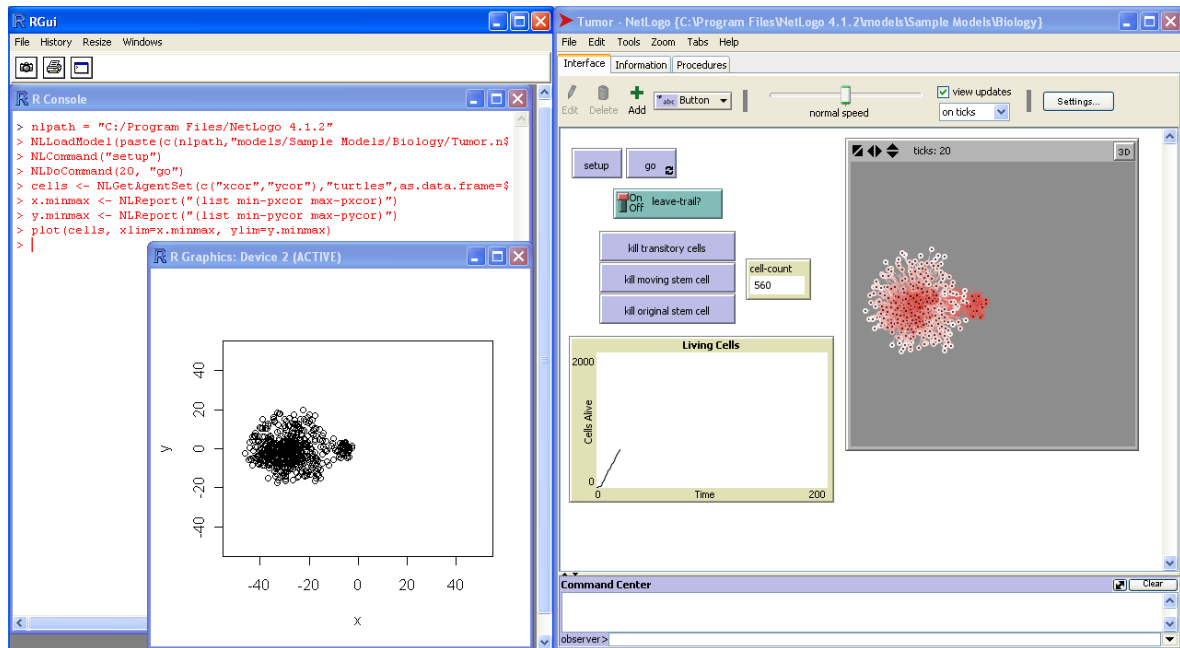


Figure 4: A visualization of turtle locations obtained via `NLGetAgentSet`. Turtle locations are displayed in the original NetLogo simulation (right) and in the R GUI of Windows (left).

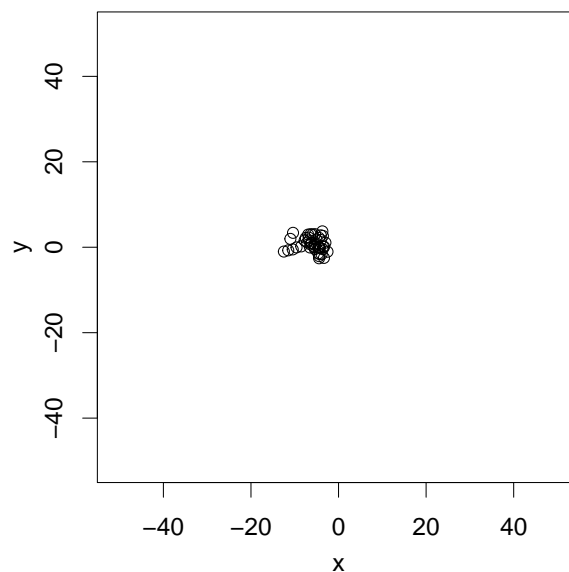


Figure 5: Same as in Figure 4 but only with a subset of turtles that fulfill a condition (are metastatic cells).

```

R> plot(cells.metastatic, xlim = x.minmax, ylim = y.minmax, xlab = "x",
+       ylab = "y")

```

We can use the `NLGetAgentSet` function to get patches and links as well. But there is a special function for patches, called `NLGetPatches`, which makes life easier by returning the

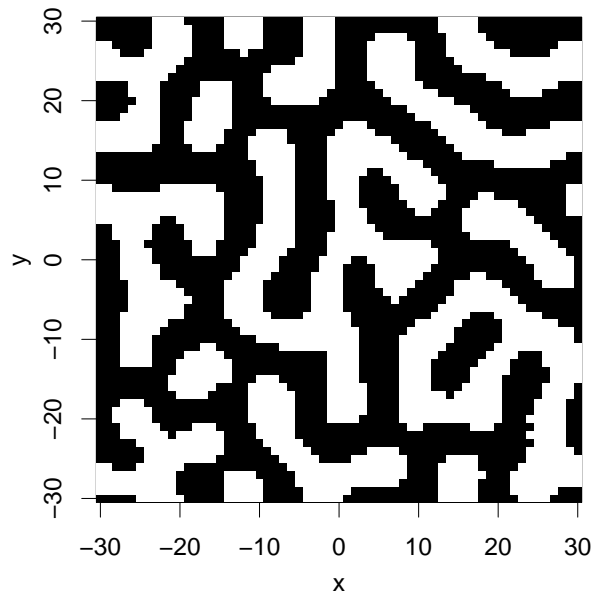


Figure 6: A simple visualization of the result of `NLGetPatches` as an image.

patch values as a matrix. We test this function by using the Fur model about patterns on animals' skin self-organization and plot the result in a simple raster image (Figure 6). We load the model, set it up and get the patches as a matrix

```
R> model.path <- file.path("models", "Sample Models", "Biology",
+   "Fur.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
R> NLCommand("setup")
R> NLDoCommand(5, "go")
R> patches.matrix <- NLGetPatches("pcolor", "patches", as.matrix = TRUE)
```

Now, we reorganize the matrix to make it fit for the image function and define the image colors:

```
R> patches.matrix.rot <- t(patches.matrix)
R> patches.matrix.rot <- as.data.frame(patches.matrix.rot)
R> patches.matrix.rot <- rev(patches.matrix.rot)
R> patches.matrix.rot <- as.matrix(patches.matrix.rot)
R> col <- c("black", "white")
```

Afterwards, we get the x and y limits (of the World) to use them for the image and draw the matrix as an image:

```
R> x.minmax <- NLReport("(list min-pxcor max-pxcor)")
R> y.minmax <- NLReport("(list min-pycor max-pycor)")
R> image(x.minmax[1]:x.minmax[2], y.minmax[1]:y.minmax[2],
+   patches.matrix.rot, col = col, xlab = "x", ylab = "y")
```

The code produced a simple raster image from the patches. It is also possible to create a spatial object from the result of `NLGetPatches` as we see in the next example, where packages `gstat` (Pebesma 2004) and `sp` (Pebesma and Bivand 2005) are used.

We start by loading the required packages and get the patches or, more precisely, the colors and coordinates of the patches:

```
R> library("sp", "gstat")
R> patches <- NLGetPatches(c("pxcor", "pycor", "pcolor"), "patches")
```

Next, we convert the patches `data.frame` to a ‘`SpatialPointsDataFrame`’ and then use this ‘`SpatialPointsDataFrame`’ to create a ‘`SpatialPixelsDataFrame`’:

```
R> coordinates(patches) <- ~ pxcor + pycor
R> gridded(patches) <- TRUE
```

Now, we convert `pcolor` to a factor, define the colors for the plot and create it (not shown here, similar to Figure 6):

```
R> patches$pcolor <- factor(patches$pcolor)
R> col <- c("black", "white")
R> spplot(patches, "pcolor", col.regions = col, xlab = "x", ylab = "y")
```

We see that it is possible to get the whole NetLogo View. As we can see in its manual page, we can save the result of `NLGetPatches` into a list, matrix or, like here, into a data frame. Furthermore, we can reduce the patches to a subset, e.g., all patches that fulfill a condition, as we have done in the `NLGetAgentSet` example.

There are two other functions that operate the other way around. With `NLSetPatches` and `NLSetPatchSet` we can push an R matrix/data frame into the NetLogo patches. `NLSetPatches` function works only if we fill all patches, i.e., if we use a matrix which has the dimension of the NetLogo World. For filling just a subset of patches we can use the `NLSetPatchSet` function.

The following example shows the usage of the `NLSetPatches` function. We reuse the `patches.matrix` variable from `NLGetPatches`, change the values from 0 (black) to 15 (red) and use this new matrix as input for the NetLogo patch variable `pcolor` (Figure 7):

```
R> my.matrix <- replace(patches.matrix, patches.matrix == 0, 15)
R> NLSetPatches("pcolor", my.matrix)
```

Another function, `NLGetGraph`, makes it possible to get a NetLogo network built by NetLogo links into an **igraph** network. This function requires the R package **igraph** (Csárdi and Nepusz 2006). As an example, we can use the Small World model from NetLogo’s Models Library. We build the NetLogo link network and transform it into an **igraph** network and finally plot it.

We start by loading as well as setting up the model and get the graph from NetLogo:

```
R> model.path <- file.path("models", "Sample Models", "Networks",
+   "Small Worlds.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
R> NLCommand("setup", "rewire-all")
R> my.network <- NLGetGraph()
```

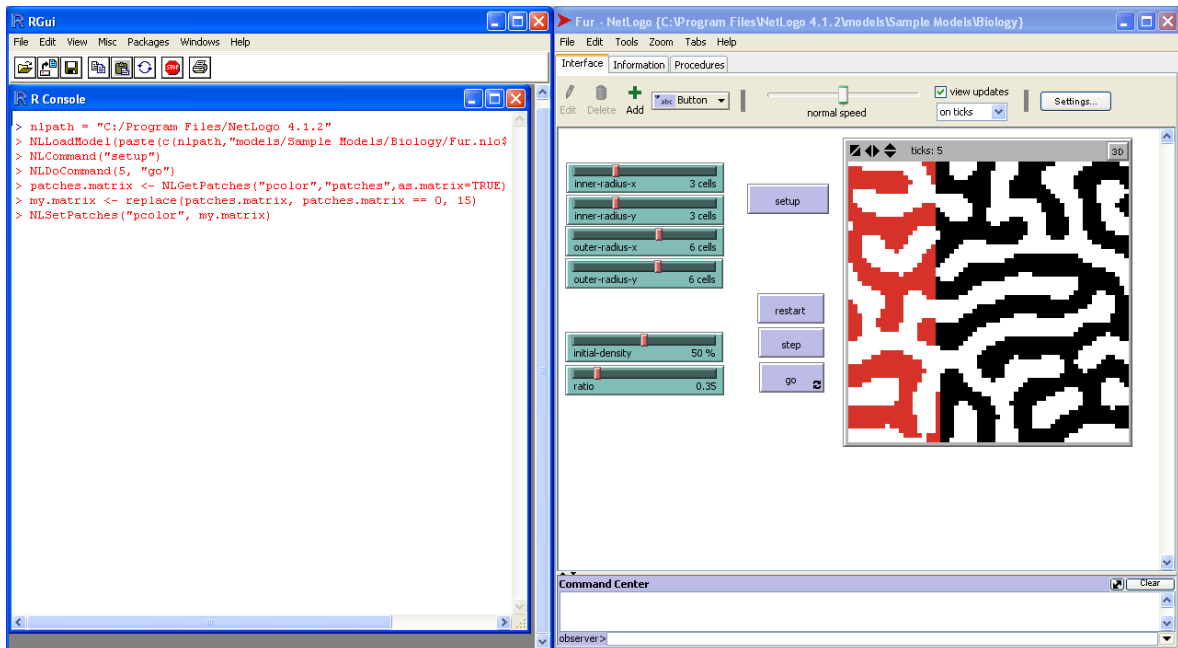


Figure 7: A screenshot while `NLSetPatches` is executing. The color of the NetLogo patches on the right hand side is changed gradually from black to red.

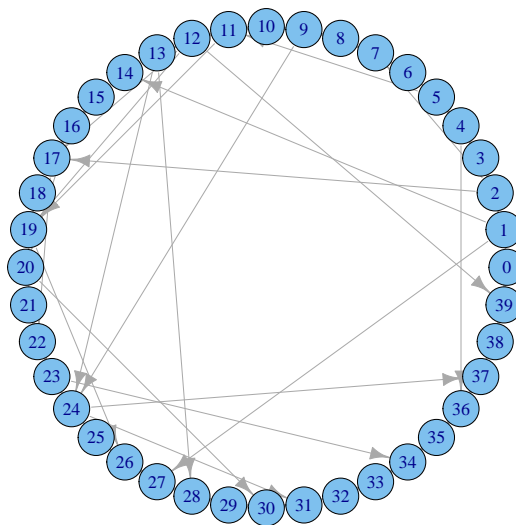


Figure 8: A graph generated by NetLogo links, sent to R via `NLGetGraph`, and plotted using the `igraph` package (Csárdi and Nepusz 2006).

Now, the directed network graph plot (Figure 8) can be obtained with:

```
R> plot(my.network, layout = layout.circle,
+       vertex.label = V(my.network)$name, vertex.label.cex = 0.7, asp = FALSE)
```


There are two further functions, which are not presented here in detail. The first one is the `NLSourceFromString` function, which enables us to create or append model source code from strings in R. A usage example is given in the code sample folder (No. 16) of the **RNetLogo** package. Another helper function to send a data frame into **NetLogo** lists is `NLDfToList`. The column names of the data frame have to be equivalent to the names of the lists in the **NetLogo** model. The code sample folder (No. 9) includes a usage example.

3.6. Headless mode/Multiple **NetLogo** instances

As mentioned above, it is possible to start **NetLogo** in background (headless mode) without a GUI. For this, we have to execute the `NLStart` function with a second argument. This will fail if we do not open a new R session (after using **RNetLogo** in GUI mode) because, as mentioned above, we cannot start several **NetLogo** sessions if we have already started one in GUI mode.

The `NLStart` function will save the **NetLogo** object reference in an internal variable in the local environment `.rnetlogo`. If we want to work with more than one **NetLogo** model/instance at once, we can specify an identifier (as a string) for the **NetLogo** instance in the third argument of `NLStart`.

We start with the creation of three **NetLogo** instances (maybe beside the one with the default identifier which is `_nl.intern_`):

```
R> my.netlogo1 <- "my.netlogo1"
R> NLStart(nl.path, gui = FALSE, nl.obj = my.netlogo1)
R> my.netlogo2 <- "my.netlogo2"
R> NLStart(nl.path, gui = FALSE, nl.obj = my.netlogo2)
R> my.netlogo3 <- "my.netlogo3"
R> NLStart(nl.path, gui = FALSE, nl.obj = my.netlogo3)
```

All functions presented until now take as last (optional) argument (`nl.obj`) a string which identifies a specific **NetLogo** instance created with `NLStart`. Therefore, we can specify which instance we want to use. When working in headless mode, the first thing to do is always to load a model. Executing a command or reporter without loading a model in headless mode will result in an error. Therefore, we load a model into all instances:

```
R> model.path <- file.path("models", "Sample Models", "Earth Science",
+   "Fire.nlogo")
R> NLLoadModel(file.path(nl.path, model.path), nl.obj = my.netlogo1)
R> NLLoadModel(file.path(nl.path, model.path), nl.obj = my.netlogo2)
R> NLLoadModel(file.path(nl.path, model.path), nl.obj = my.netlogo3)
```

Now, we will set up and run the models over different simulation times. We run the first instance (`my.netlogo1`) for 25 ticks:

```
R> NLCommand("setup", nl.obj = my.netlogo1)
R> NLDoCommand(25, "go", nl.obj = my.netlogo1)
```

Then, we run the second instance (`my.netlogo2`) for 15 ticks:

```
R> NLCommand("setup", nl.obj = my.netlogo2)
R> NLDoCommand(15, "go", nl.obj = my.netlogo2)
```

and we simulate 5 ticks with the third instance:

```
R> NLCommand("setup", nl.obj = my.netlogo3)
R> NLDoCommand(5, "go", nl.obj = my.netlogo3)
```

To check if the above worked well, we compare the number of burned trees in the different instances, which should be different:

```
R> NLReport("burned-trees", nl.obj = my.netlogo1)
```

```
[1] 1560
```

```
R> NLReport("burned-trees", nl.obj = my.netlogo2)
```

```
[1] 929
```

```
R> NLReport("burned-trees", nl.obj = my.netlogo3)
```

```
[1] 423
```

At the end, we quit the NetLogo sessions (the standard session with internal identifier `_nl.intern_` as well, if open):

```
R> NLQuit(nl.obj = my.netlogo3)
R> NLQuit(nl.obj = my.netlogo2)
R> NLQuit(nl.obj = my.netlogo1)
R> NLQuit()
```

4. Application examples

The following examples are (partly) inspired by the examples presented for the **NetLogo-Mathematica Link** (see [Bakshy and Wilensky 2007b](#)). These are all one-directional examples (from NetLogo to R), but the package opens up the possibility of letting NetLogo and R interact and send back results from R (e.g., statistical analysis) to NetLogo and let the model react to them. Even manipulation of the model source by using the `NLSourceFromString` function is possible. This opens up the possibility to generate NetLogo code from R dynamically.

4.1. Exploratory analysis

A simple parameter sensitivity experiment illustrates exploratory analysis with **RNetLogo**, even though NetLogo has a very powerful built-in tool, **BehaviorSpace** ([Wilensky 2012](#)), for this simple kind of experiment. Here, we will use the Forest Fire model ([Wilensky 1997a](#)) from NetLogo's Models Library and explore the effect of the density of trees in the forest on the percentage of burned trees as described in [Bakshy and Wilensky \(2007b\)](#).

We start, as always, by loading and initializing the package (if not already done) and model:

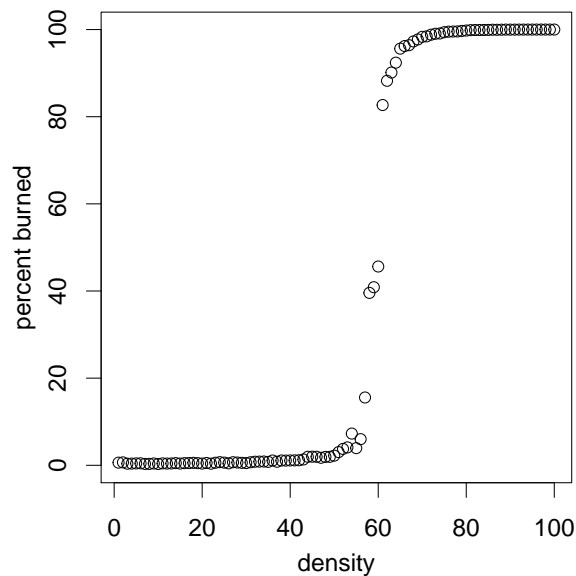


Figure 9: Results of the Forest Fire model varying the density of trees. The y -axis is the percentage of burned trees after no burning patches (i.e., no turtles) were left in the simulation.

```
R> library("RNetLogo")
R> nl.path <- file.path(getwd(), "NetLogo 5.0.5")
R> NLStart(nl.path, gui = FALSE)
R> model.path <- file.path("models", "Sample Models", "Earth Science",
+   "Fire.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
```

Next, we define a function which sets the density of trees, executes the simulation until no turtles are left, and reports back the percentage of burned trees:

```
R> sim <- function(density) {
+   NLCommand("set density ", density, "setup")
+   NLDoCommandWhile("any? turtles", "go");
+   ret <- NLReport("(burned-trees / initial-trees) * 100")
+   return(ret)
+ }
```

We run the simulation for density values between 1 and 100 with a step size of 1, to identify the phase transition (Figure 9):

```
R> d <- seq(1, 100, 1)
R> pb <- sapply(d, function(dens) sim(dens))
R> plot(d, pb, xlab = "density", ylab = "percent burned")
```

As we know the region of phase transition (between a density of 45 and 70 percent), we can explore this region more precisely. As the Forest Fire model uses random numbers, it is interesting to find out how much stochastic variation occurs in this region. Therefore, we define a function to repeat the simulations with one density several times:

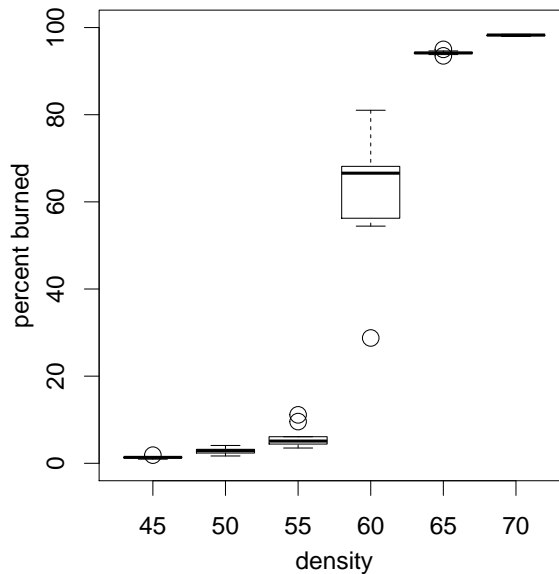


Figure 10: Boxplots of repeated simulations (10 replications) with the Forest Fire model with varying density (45–70 percent) of trees and the percentage of burned trees after no turtles were left in the simulation.

```
R> rep.sim <- function(density, rep)
+   lapply(density, function(dens) replicate(rep, sim(dens)))
```

To get a rough overview we use this new function for densities between 45 and 70 percent with a step size of 5, and 10 replications each (Figure 10):

```
R> d <- seq(45, 70, 5); res <- rep.sim(d, 10)
R> boxplot(res, names = d, xlab = "density", ylab = "percent burned")
```

Now, we have seen that the variation of burned trees at densities below 55 and higher than 65 is low. As a result, we can skip these values and have a deeper look into the region of density values between 55 and 65. Therefore, we perform a simulation experiment for this value range with a smaller step size of 1 percent and a higher amount of replication of 20 per density value (Figure 11):

```
R> d <- seq(55, 65, 1); res <- rep.sim(d, 20)
R> boxplot(res, names = d, xlab = "density", ylab = "percent burned")
```

4.2. Database connection

There are R packages available to connect R to all common database management systems, e.g., **RMySQL** (James and DeRoy 2012), **RPostgreSQL** (Conway, Eddelbuettel, Nishiyama, Sameer, and Tiffin 2012), **ROracle** (Mukhin, James, and Luciani 2012), **RJDBC** (Urbanek 2011), **RSQLite** (James 2011) or **RODBC** (Ripley 2012). Thus the **RNetLogo** package opens up the possibility to store the simulation results into a database.

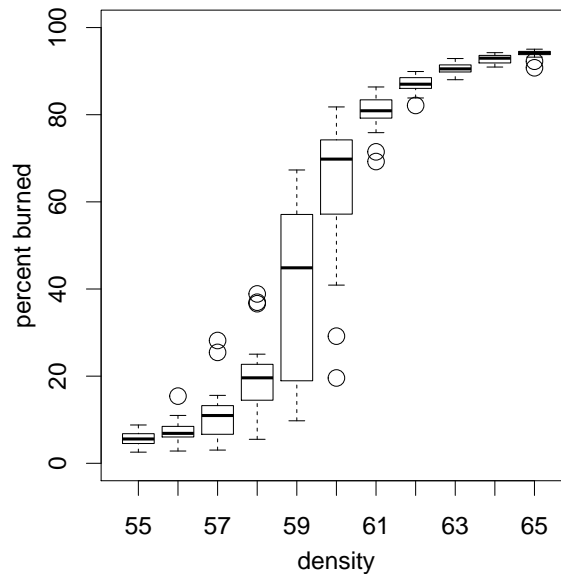


Figure 11: Boxplots of repeated simulations (20 replications) with the Forest Fire model with varying density (55–65 percent) of trees and the percentage of burned trees after no turtles were left in the simulation.

In the following example we use the **RSQLite** package (James 2011), which provides a connection to **SQLite** databases (Hipp 2012), because this is a very easy-to-use database in a single file. It does not need a separate database server and is, therefore, ideal for agent-based modeling studies, where no large database management systems (DBMS) are used. The database can store the results of different simulation experiments in different tables together with metadata in one file. This makes it very easy to share simulation results. There are small and easy-to-use GUI programs available to browse and edit **SQLite** databases; see, for example, the **SQLite** Database Browser (Piacentini 2012).

In a first step we have to set up the connections to **NetLogo** (if not already done) and load as well as initialize the example model:

```
R> library("RNetLogo")
R> nl.path <- file.path(getwd(), "NetLogo 5.0.5")
R> NLStart(nl.path, gui = FALSE)
R> model.path <- file.path("models", "Sample Models", "Earth Science",
+   "Fire.nlogo")
R> NLLoadModel(file.path(nl.path, model.path))
R> NLCommand("setup")
```

Then, we load the required **RSQLite** package and database driver as well as create a connection to the database. If the database does not exist, this creates a file `test_netlogo.db`:

```
R> library("RSQLite")
R> m <- dbDriver("SQLite")
R> database.path = "test_netlogo.db"
R> con <- dbConnect(m, dbname = database.path)
```

Next, we run the model for ten ticks and save the results (ticks and burned-trees) in the table `Burned1` of the database:

```
R> dbWriteTable(con, "Burned1",
+   NLDoreport(10, "go", c("ticks", "burned-trees"),
+   as.data.frame = TRUE, df.col.names = c("tick", "burned")),
+   row.names = FALSE, append = FALSE)
```

Afterwards, we can send a first query: how many lines has the new table?

```
R> dbGetQuery(con, "select count(*) from Burned1")[[1]]
```

```
[1] 10
```

In the second query, we select all rows from table `Burned10` where `tick` is greater than 5:

```
R> rs <- dbSendQuery(con, "select * from Burned1 where tick > 5")
```

Then, we ask for the result of the query and print it:

```
R> data <- fetch(rs, n = -1)
R> str(data)
```

```
'data.frame':      5 obs. of  2 variables:
 $ tick  : num  6 7 8 9 10
 $ burned: num  458 513 564 627 682
```

Next, we delete/clear the query:

```
R> dbClearResult(rs)
```

Afterwards, we append further results to the existing table:

```
R> dbWriteTable(con, "Burned1",
+   NLDoreport(10, "go", c("ticks", "burned-trees"),
+   as.data.frame = TRUE, df.col.names = c("tick", "burned")),
+   row.names = FALSE, append = TRUE)
```

and take a look at the table:

```
R> select.all <- dbGetQuery(con, "select * from Burned1")
R> str(select.all)
```

```
'data.frame':      20 obs. of  2 variables:
 $ tick  : num  1 2 3 4 5 6 7 8 9 10 ...
 $ burned: num  134 205 273 343 404 458 513 564 627 682 ...
```

Now, we create a second table and save the results of ten repeated simulations of 20 ticks each:

```
R> for (x in 1:10) {
+   NLCommand("setup")
+   dbWriteTable(con, "Burned2",
+     NLDoReport(20, "go", c("ticks", "burned-trees"),
+     as.data.frame = TRUE, df.col.names = c("tick", "burned")),
+     row.names = FALSE, append = TRUE)
+ }
```

and calculate the mean number of burned trees (out of the 10 repetitions) for each tick, get the result of the query and show it:

```
R> rs <- dbSendQuery(con,
+   "select avg(burned) as mean_burned from Burned2 group by tick")
R> data <- fetch(rs, n = -1)
R> str(data)
```

```
'data.frame':      20 obs. of  1 variable:
 $ mean_burned: num  146 228 310 385 452 ...
```

Finally, we delete/clear the query and close the connection to the database:

```
R> dbClearResult(rs); dbDisconnect(con)
```

Note that there is also an extension to connect databases directly to NetLogo (see <http://code.google.com/p/netlogo-sql/>).

4.3. Analytical comparison

The example application of Bakshy and Wilensky (2007b) compares results of an agent-based model of gas particles to velocity distributions found by analytical treatments of ideal gases. To reproduce this, we use the Free Gas model (Wilensky 1997b) of the GasLab model family from NetLogo's Models Library. In this model, gas particles move and collide with each other without external constraints. Bakshy and Wilensky (2007b) compared this model's results to the classical Maxwell-Boltzmann distribution. R itself is not a symbolic mathematical software but there are packages available which let us integrate such software. Here, we use the **Ryacac** package (Goedman, Grothendieck, Højsgaard, and Pinkus 2010) which is an interface to the open-source Yacas Computer Algebra System (Pinkus, Winitzki, and Niesen 2007).

We start with the agent-based model simulation. Because this model is based on random numbers we run repeated simulations.

We start with loading and initializing the **RNetLogo** package (if not already done) and the model:

```
R> library("RNetLogo")
R> nl.path <- file.path(getwd(), "NetLogo 5.0.5")
R> NLStart(nl.path, gui = FALSE)
R> model.path1 <- file.path("models", "Sample Models", "Chemistry & Physics",
+   "GasLab")
```

```
R> model.path2 <- "GasLab Free Gas.nlogo"
R> NLLoadModel(file.path(nl.path, model.path1, model.path2))
R> NLCommand("set number-of-particles 500", "no-display", "setup")
```

Next, we run the simulation for 40 times of 50 ticks (= 2000 ticks), save the speed of the particles after every 50 ticks, and flatten the list of lists (one list for each of the 40 runs) to one big vector:

```
R> particles.speed <- NLDoReport(40, "repeat 50 [go]",
+   "[speed] of particles")
R> particles.speed.vector <- unlist(particles.speed)
```

To calculate the analytical distribution, we have to solve the following equations:

$$B(v) = v \cdot e^{(-m \cdot v)^2 \cdot (2 \cdot k \cdot T)^{-1}} \quad (1)$$

$$normalizer = \int_0^{\infty} B(v) dv \quad (2)$$

$$B(v)_{normalized} = \frac{B(v)}{normalizer} \text{ for } v = [0, \max(speed)] \quad (3)$$

Now, **Yacas**/**Ryacas** will be used. For this, we define Equation 1 with the mean energy derived from the NetLogo simulation. We then define the normalizer integral and solve it numerically.

We start by loading the **Ryacas** package:

```
R> library("Ryacas")
```

We can install Yacas, if currently not installed (only for Windows – see **Ryacas**/**Yacas** documentation for other systems) with:

```
R> yacasInstall()
```

Next, we get the mean energy from the NetLogo simulation and define the function B and register it in Yacas:

```
R> energy.mean <- NLReport("mean [energy] of particles")
R> B <- function(v, m = 1, k = 1)
+   v * exp((-m * v^2) / (2 * k * energy.mean))
R> yacas(B)
```

Then, we define the integral of function B from 0 to infinity and register the integral expression in Yacas:

```
R> B.integr <- expression(integrate(B, 0, Infinity))
R> yacas(B.integr)
```

Now, we calculate a numerical approximation using Yacas's function N() and get the result from Yacas in R (the result is in the list element `value`):

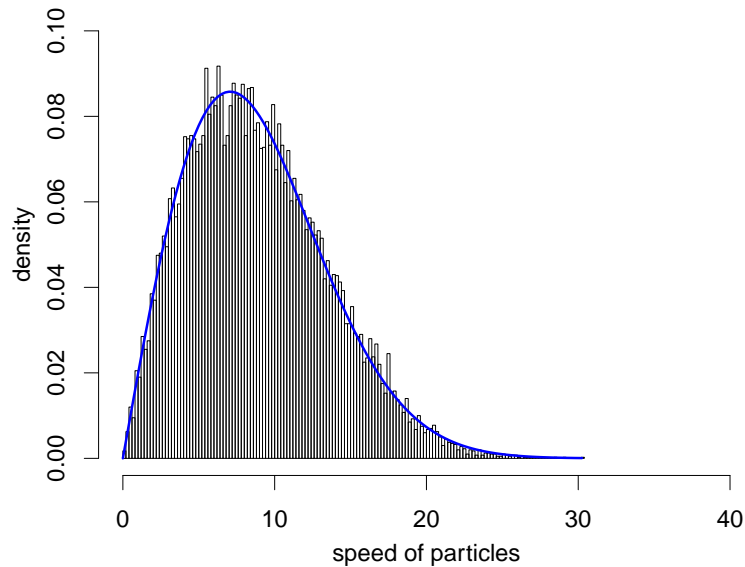


Figure 12: Empirical probability distribution of particle speeds generated by the agent-based model (bars) with the theoretical Maxwell-Boltzmann distribution (blue line).

```
R> normalizer.yacas <- yacas(N(B.integr))
R> normalizer <- Eval(normalizer.yacas)
R> print(normalizer$value)
```

```
[1] 50
```

In a further step, we calculate the theoretical probability values of particle speeds using Equation 1. We do this from 0 to the maximum speed observed in the NetLogo simulation.

First, we get the maximum speed from the NetLogo simulation:

```
R> maxspeed <- max(particles.speed.vector)
```

Next, we create a sequence vector from 0 to maxspeed, by stepsize, and calculate the theoretical values at the points of the sequence vector:

```
R> stepsize <- 0.25
R> v.vec <- seq(0, maxspeed, stepsize)
R> theoretical <- B(v.vec) / normalizer$value
```

At the end, we plot the empirical/simulation distribution together with the theoretical distribution of particle speeds (Figure 12):

```
R> hist(particles.speed.vector, breaks = max(particles.speed.vector) * 5,
+     freq = FALSE, xlim = c(0, as.integer(maxspeed) + 5),
+     ylab = "density", xlab = "speed of particles", main = "")
R> lines(v.vec, theoretical, lwd = 2, col = "blue")
```

4.4. Advanced plotting functionalities

R and its packages deliver a wide variety of plotting capabilities. As an example, we present a three-dimensional plot in combination with a contour map. We use the “Urban Site – Sprawl Effect” model (Felsen and Wilensky 2007) from NetLogo’s Models Library. This model simulates the growth of cities and urban sprawl. Seekers (agents) look for patches with high attractiveness and also increase the attractiveness of the patch they stay on. Therefore, the attractiveness of the patches is a state variable of the model, which can be plotted in R.

First, we initialize the **RNetLogo** package (if not already done) and load the model:

```
R> library("RNetLogo")
R> nl.path <- file.path(getwd(), "NetLogo 5.0.5")
R> NLStart(nl.path, gui = FALSE)
R> model.path <- file.path("models", "Curricular Models", "Urban Suite")
R> model.name <- "Urban Suite - Sprawl Effect.nlogo"
R> NLLoadModel(file.path(nl.path, model.path, model.name))
```

We resize NetLogo’s World and set the parameter values:

```
R> NLCommand("resize-world -20 20 -20 20")
R> NLCommand("set smoothness 10", "set max-attraction 5",
+ "set population 500", "set seeker-search-angle 200",
+ "set seeker-patience 15", "set wait-between-seeking 5")
```

Then, we set up the simulation and run it for 150 ticks:

```
R> NLCommand("setup"); NLDoCommand(150, "go")
```

Next, we get the value of the variable `attraction` from all patches as a matrix as well as the dimensions of NetLogo’s World:

```
R> attraction <- NLGetPatches("attraction", as.matrix = TRUE)
R> pxcor <- NLReport(c("min-pxcor", "max-pxcor"))
R> pycor <- NLReport(c("min-pycor", "max-pycor"))
```

Now, we define the advanced plotting function with a three-dimensional plot and a contour map (adapted from Francois 2011):

```
R> kde2dplot <- function(d, ncol = 50, zlim = c(0, max(z)),
+   nlevels = 20, theta = 30, phi = 30) {
+   z <- d$z
+   nrz <- nrow(z)
+   ncz <- ncol(z)
+   colors <- tail(topo.colors(trunc(1.4 * ncol)), ncol)
+   fcol <- colors[trunc(z / zlim[2] * (ncol - 1)) + 1]
+   dim(fcol) <- c(nrz, ncz)
+   fcol <- fcol[-nrz, -ncz]
+   par.default <- par(no.readonly = TRUE)
```

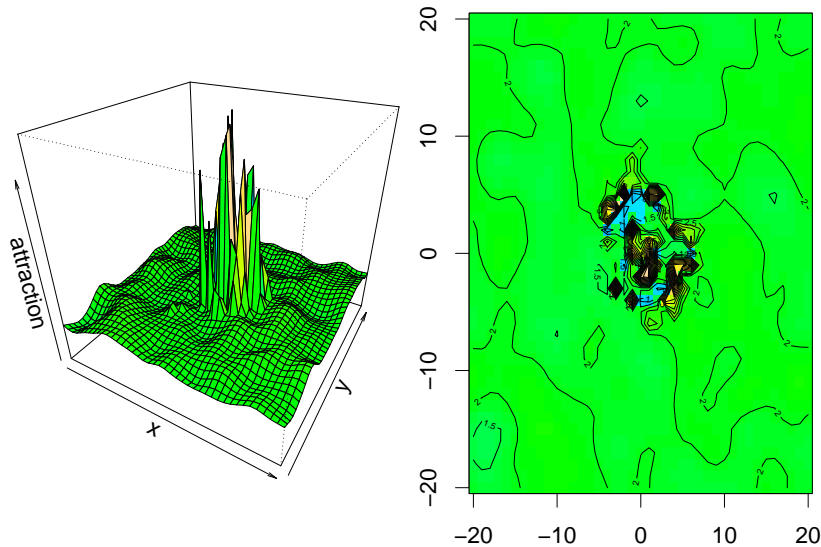


Figure 13: Spatial distribution of attractiveness of patches after 150 simulation steps. 3D plot (left) and contour plot (right).

```
+   par(mfrow = c(1, 2), mar = c(0, 0, 0, 0), cex = 1.5)
+   persp(d, col = fcol, zlim = zlim, theta = theta, phi = phi,
+         zlab = "attraction", xlab = "x", ylab = "y")
+   par(mar = c(2, 2, 0.5, 0.5))
+   image(d, col = colors)
+   contour(d, add = TRUE, nlevels = nlevels)
+   box()
+   par(par.default)
+ }
```

We merge the data and execute the plot function (Figure 13):

```
R> d <- list(x = seq(pxcor[[1]], pxcor[[2]]),
+           y = seq(pycor[[1]], pycor[[2]]), z = attraction)
R> kde2dplot(d)
```

4.5. Time sliding visualization

As agent-based models are often very complex, more than three dimensions could be relevant for their analysis. With the **RNetLogo** package it is possible to save the output of a simulation in R for every tick and then click through, or animate, the time series of these outputs, for example a combination of the model's View and distributions of state variables. As a prototype, we write a function to implement a timeslider to plot turtles. This function can be extended to visualize a panel of multiple plots by tick. With a slider we can browse through the simulation steps. To give an example, we use the Virus model (Wilensky 1998) from NetLogo's Models Library to visualize the spatial distribution of infected and immune agents as well as boxplots of the time period of infection and the age in one plot panel.

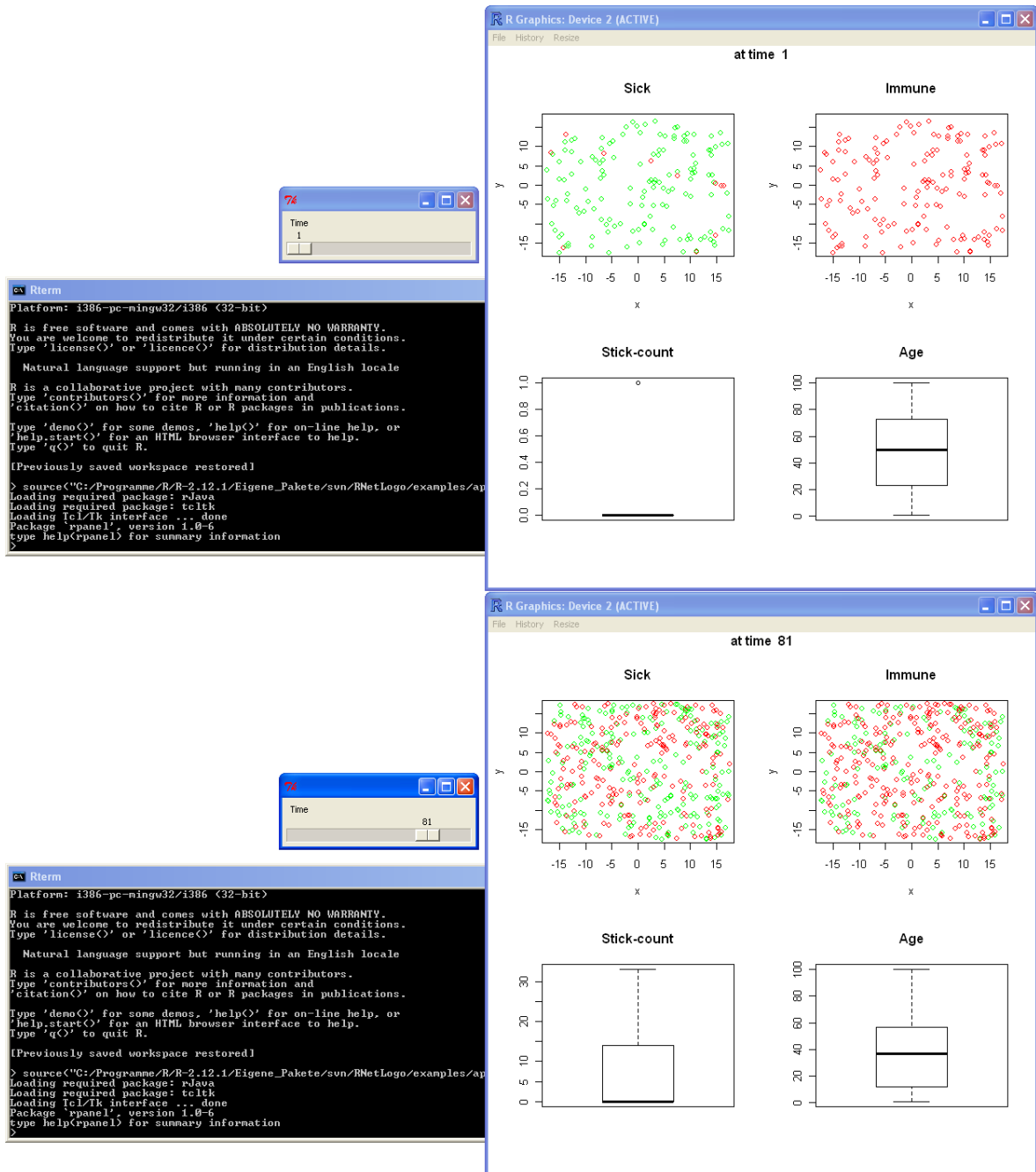


Figure 14: Timeslider example using the Virus model.

We first load the required package **rpanel** (Bowman, Crawford, Alexander, and Bowman 2007) and define a helper function to set the plot colors for the logical variables (sick, immune) of the turtles:

```
R> library("rpanel")
R> color.func <- function(color.var, colors, timedata) {
+   color <- NULL
```

```

+   if (!is.null(color.var)) {
+     index.color <- which(names(timedata) == color.var)
+     color <- timedata[[index.color]]
+     color[color == FALSE] <- colors[1]
+     color[color == TRUE] <- colors[2]
+   }
+   return(color)
+ }

```

Next, we define the main function containing the slider and what to do if we move the slider. The input is a list containing data frames for every tick. When the slider is moved, we send the current position of the slider (i.e., the requested tick) to the plotting function, extract the corresponding data frame from the `timedata` list and draw a panel of four plots using this data frame.

```

R> plottimedata <- function(timedata.list, x.var, y.var, boxplot.var1,
+   boxplot.var2, color.var1 = NULL, colors1 = "black",
+   color.var2 = NULL, colors2 = "black", mains = NULL, ...) {
+   timeslider.draw <- function(panel) {
+     index.x <- which(names(timedata.list[[panel$t]]) == x.var)
+     index.y <- which(names(timedata.list[[panel$t]]) == y.var)
+     index.b1 <- which(names(timedata.list[[panel$t]]) == boxplot.var1)
+     index.b2 <- which(names(timedata.list[[panel$t]]) == boxplot.var2)
+
+     color1 <- color.func(color.var1, colors1, timedata.list[[panel$t]])
+     color2 <- color.func(color.var2, colors2, timedata.list[[panel$t]])
+
+     par(mfrow = c(2, 2), oma = c(0, 0, 1, 0))
+     plot(timedata.list[[panel$t]][[index.x]],
+         timedata.list[[panel$t]][[index.y]], col = color1,
+         main = mains[1], ...)
+     plot(timedata.list[[panel$t]][[index.x]],
+         timedata.list[[panel$t]][[index.y]], col = color2,
+         main = mains[2], ...)
+     boxplot(timedata.list[[panel$t]][[index.b1]], main = mains[3])
+     boxplot(timedata.list[[panel$t]][[index.b2]], main = mains[4])
+     title(paste("at time ", panel$t), outer = TRUE)
+     panel
+   }
+   panel <- rp.control()
+   rp.slider(panel, resolution = 1, var = t, from = 1,
+     to = length(timedata.list), title = "Time", showvalue = TRUE,
+     action = timeslider.draw)
+ }

```

In the third step, we initialize and run the NetLogo simulation and collect the results into the `timedata` list. As mentioned above, we push a data frame containing the results of one tick

into the `timedata` list. Here, we run 100 ticks and use the `NLGetAgentSet` function to collect data from the turtles.

```
R> library("RNetLogo")
R> nl.path <- file.path(getwd(), "NetLogo 5.0.5")
R> model.path <- file.path("models", "Sample Models", "Biology",
+   "Virus.nlogo")
R> NLStart(nl.path)
R> NLLoadModel(file.path(nl.path, model.path))
R> NLCommand("setup")
R> nruns <- 100
R> timedata <- list()
R> for(i in 1:nruns) {
+   NLCommand("go")
+   timedata[[i]] <- NLGetAgentSet(c("who", "xcor", "ycor", "age",
+     "sick?", "immune?", "sick-count"), "turtles")
+ }
```

In the last step, we collect the dimension of the NetLogo World to use it for the axis extent of the plot and define the colors used for the variables `sick` (`green = FALSE`, `red = TRUE`) and `immune` (`red = FALSE`, `green = TRUE`). Finally, we call the above-defined `plottimedata` function to create the timeslider.

```
R> world.dim <- NLReport(c("(list min-pxcor max-pxcor)",
+   "(list min-pycor max-pycor)"))
R> colors1 <- c("green", "red")
R> colors2 <- c("red", "green")
R> plottimedata(timedata.list = timedata, x.var = "xcor", y.var = "ycor",
+   xlab = "x", ylab = "y", color.var1 = "sick?", color.var2 = "immune?",
+   boxplot.var1 = "sick-count", boxplot.var2 = "age", colors1 = colors1,
+   colors2 = colors2, mains = c("Sick", "Immune", "Sick-count", "Age"),
+   xlim = world.dim[[1]], ylim = world.dim[[2]])
```

Then we can move the slider and the plot is updated immediately (Figure 14).

5. Pitfalls

5.1. Amount of data

Please note that we are not able to stop the execution of a NetLogo command without closing our R session. Therefore, it is a good idea to think about the amount of data which should be transformed. For example, if we use the `NLGetPatches` function with the standard settings of the Forest Fire model from NetLogo's Models Library, we are requesting 63001 patch values. If we ask for the `pxcor`, `pycor` and `pcolor` values, we are requesting for $63001 \cdot 3 = 189003$ values. All these values have to be transformed from NetLogo data type to Java and from Java to R. This may take a while. For technical reasons, we are not informed about the progress of

NetLogo	R
Boolean	Boolean
String	String
Number	Double
List of strings	Vector of strings
List of booleans	Vector of booleans
List of numbers	Vector of doubles
Nested list (one nesting)	List of vectors
Nested list (multi-level nesting)	List of lists, lowest level: vectors

Table 2: Mapping from NetLogo data types to R data types.

data transformation. Therefore, it looks like the program crashed, but if we are patient, the program will return with the result after some time. Thus it is always a good idea to test the code with a very small example (i.e., small worlds, low number of agents etc.). As mentioned in Section 3.2, NetLogo 5.0.x is much faster at transferring data than NetLogo 4.x.

5.2. Endless loops

If we use the functions `NLDoCommandWhile` and `NLDoReportWhile`, we should double check our while-condition. Are we sure that the condition will be met some time? To prevent endless loops, these functions take an argument `max.minutes` with a default value of 10. This means that the execution of these functions will be interrupted if it takes longer than the submitted number of minutes. If we are sure that we do not submit something that will trigger an endless loop, we can switch off this functionality by using a value of 0 for the `max.minutes` argument. This will speed up the operation because the time checking operation will not be applied.

5.3. Data type

The general mapping of NetLogo data types to R data types in **RNetLogo** is given in Table 2. We should think about the data types we are trying to combine. For example, an R vector takes values of just one data type (e.g., string, numeric/double or logical/boolean) unlike a NetLogo list, which can contain different data types. Here are some examples.

First, we get a NetLogo list of numbers:

```
R> NLReport("(list 24 23 22)")
```

Second, we get a NetLogo list of strings:

```
R> NLReport("(list \"foo1\" \"foo2\" \"foo3\")")
```

Third, we try to get a NetLogo list of combined numbers and a string:

```
R> NLReport("(list 24 \"foo\" 22)")
```

The first two calls of `NLReport` will run as expected but the last call will throw an error, because `NLReport` tries to transform a NetLogo list into an R vector, which will fail due to the mixed data types. This is also relevant in particular for the columns of `data.frames`.

Call	Output of <code>str(<Call>)</code>
<code>NLDoReport(2, "go", "(list count fires count embers)")</code>	List of 2 \$: num [1:2] 2 2 \$: num [1:2] 0 4
<code>NLDoReport(2, "go", c("count fires", "count embers"))</code>	List of 2 \$:List of 2 ..\$: num 2 ..\$: num 2 \$:List of 2 ..\$: num 0 ..\$: num 4

Table 3: Examples of results of `NLDoReport` with different `NetLogo` data structures. The Forest Fire model is used with a world of only 3×3 patches and a density of 99 percent. The model is reset before each example.

5.4. Data structure

Since `RNetLogo` does not restrict how `NetLogo` reporters are combined, it is very flexible but makes it necessary to think very carefully about the data structure that will be returned. How a `NetLogo` value is transformed in general is already defined in Table 2.

But this becomes more complex for iteration functions like `NLDoReport` where the return values of one iteration are combined with the results of another iteration, especially when requesting the result as a data frame instead of a list.

For example, it makes a difference in the returned data structure when we request two values as a `NetLogo` list or as two single reporters in a vector (Table 3). Requesting the values as a `NetLogo` list returns a top-level list containing a vector of two values for all requested iterations. Requesting two single reporters returns these in a list as an entry of a top-level list. Therefore, this results in a nested list structure. There is not a wrong or preferred solution, it just depends on what we want to do with the result.

Requesting the result of `NLDoReport` as a data frame converts the top-level list to a data frame in a way that the top-level list entries become columns of the data frame and one iteration is represented by a row. This becomes problematic when nested `NetLogo` lists are requested (Table 4). In such a case, the nested `NetLogo` lists are transformed into R lists and the resulting data frame contains lists in its columns. Such a data structure is a valid, but uncommon, data frame and some functions, like `write.table`, can operate only with a data frame that contains just simple objects in its columns. To make a data frame with nested lists fit for functions like `write.table` we have to use the `I(x)` function for the affected columns to treat them 'as is' (see `help(I)` for details, e.g., `my.df$col1 <- I(my.df$col1)`).

Furthermore, using an agentset in an `NLDoReport` iteration with data frame return value can become problematic. As long as the number of members of the agentset does not change, it can be requested without problems in a data frame. The data frame contains one column for each agent and one row for each iteration. If the number of agents changes during the iterations the resulting data frame is not correct as it contains entries that do not exist. The number of columns equals the maximum number of agents over all iterations. For those iterations that

Call	Output of <code>str(<Call>)</code>
<code>NLDoReport(2, "go", "(list count fires count embers)", as.data.frame = TRUE)</code>	'data.frame': 2 obs. of 2 variables: \$ X1: num 0 0 \$ X2: num 4 4
<code>NLDoReport(2, "go", c("count fires", "count embers"), as.data.frame = TRUE)</code>	'data.frame': 2 obs. of 2 variables: \$ X1: num 0 0 \$ X2: num 4 4
<code>NLDoReport(2, "go", c("count turtles", "(list count fires count embers)"), as.data.frame = TRUE)</code>	'data.frame': 2 obs. of 2 variables: \$ X1: num 4 4 \$ X2:List of 2 ..\$: num 0 4 ..\$: num 0 4

Table 4: Examples of results of `NLDoReport` with different NetLogo data structures. The Forest Fire model is used with a world of only 3×3 patches and a density of 99 percent. The model is reset before each example.

contain less agents the columns of the data frame are filled with copied information from a former column. In short, the information is wrong. The following example illustrates this. The Forest Fire model is used with a world of only 5×3 patches.

```
R> res <- NLDoReport(3, "go", "[who] of turtles", as.data.frame = TRUE)
R> str(res)
```

```
'data.frame':      3 obs. of  7 variables:
 $ X1: num  2 4 0
 $ X2: num  0 2 6
 $ X3: num  3 0 4
 $ X4: num  1 3 1
 $ X5: num  2 1 5
 $ X6: num  0 4 3
 $ X7: num  3 2 2
```

The first iteration contains four turtles, the second five and the third seven turtles. The returned data frame therefore contains seven columns. Entries in columns for the first and the second row (i.e., iteration) are repeated from the first columns. But fortunately we are warned by R that the length of the vectors differ. When we cannot be sure that the number of return values is always the same over the iterations we should use the default list data structure instead of the data frame return structure. Furthermore, if we want to request an agentset, we should better use the `NLGetAgentSet` function in an R loop, as shown in Section 4.5, because it returns the requested values in a sorted order; for agents by their `who` number and in case of patches from upper left to lower right.

These examples illustrate that it is necessary to think about the data structure that is required for further analyses and which function can process such a data structure.

5.5. Working directory

We should avoid changing the working directory of R manually, because **NetLogo** needs to have the working directory pointed to its installation path. As the R working directory and the **Java** working directory depend on each other, changing the R working directory can result in unexpected behavior of **NetLogo**. Therefore, we should use absolute paths for I/O processes in R instead of submitting `setwd(...)`. Note that the **RNetLogo** package changes the working directory automatically when loading **NetLogo** and changes back to the former working directory when the last active **NetLogo** instance is closed with `NLQuit`.

6. Discussion

This article gave a theoretical and practical introduction to the **RNetLogo** package. The reader should be well-prepared to start his/her own projects based on **RNetLogo** after studying the examples. Since there are so many interesting packages available in R with connections to many other programs, it is really amazing what this connection offers to both, R users and **NetLogo** users.

Note that there are code samples for all functions in the example folder (`RNetLogo/examples/code_samples`) of the **RNetLogo** package. Furthermore, there are some example applications in the example folder, similar to those presented here.

As presented the **RNetLogo** package successfully links the statistical computing environment R with the agent-based modeling platform **NetLogo**. Thereby it brings together the world of statistics and data analysis with the world of agent-based modeling. From the viewpoint of an R user it opens up the possibility to access a rule-based modeling language and environment. Therefore, (nearly) all types of agent-based and system-dynamics models can be easily embedded into R. **NetLogo**'s Models Library gives a nice impression of what kind of models can be built, from deterministic to stochastic, from non-spatial to spatial models, from 2D to 3D, from cellular automata over network models and artificial neural networks to L-systems and many others more.

Bringing simulation models to R is not entirely new. There are, on the one hand, other modeling environments, like **Repast** (North, Collier, and Vos 2006), that open the possibility to send data to R. But the ability to control simulation experiments from R is new for such modeling tools. **NetLogo** was selected because it is very easy to learn, very well designed, and much better documented than other ABM platforms. It has a very active user community and seems to be the most appropriate basis for all kinds of modelers, from beginners to professionals and from ecology over social sciences to informatics. On the other hand, there are packages available to build simulation models directly in R, like **simecol** (Petzoldt and Rinke 2007). Especially **simecol** is fast and very flexible and a good choice in comparison to implementations in pure R but it does not provide specific support for making model development and simulation efficient as agent-based model environments like **NetLogo** and **Repast** do.

Some first use-cases of **RNetLogo** have been presented in this article. Beside the advanced visualization possibilities and connections to other software an important application area is

the design and analysis of simulation experiments in a systematic, less ad-hoc, way. R delivers all necessary functions of the design of experiments (DoE) principles. With **RNetLogo** the technical connection between all kinds of DoE and ABM is available.

There are already ready-to-use solutions for model analysis/DoE techniques available for agent-based modeling, like **BehaviorSearch** (Stonedahl and Wilensky 2013), **MEME** (Iványi, Gulyás, Bocsi, Szemes, and Mészáros 2007), and **openMOLE** (Reuillon, Chuffart, Leclaire, Faure, Dumoulin, and Hill 2010), but they are less flexible and adaptable than R. Often, for one task, several packages in R are available and if not, writing own functions is flexible and fast, especially because many scientists know R already from its application for data analysis. Since **RNetLogo** does not restrict the user to predefined analysis functions it opens up a large flexibility. But **RNetLogo** can only check the submitted **NetLogo** code strings at runtime. This is a disadvantage, although the **NetLogo** code strings are typically simple and lack of automated checking encourages well-designed analysis. Nevertheless, **RNetLogo** requires the user to understand data types and structures of both **NetLogo** and R.

RNetLogo pushes the documentation and therefore the reproducibility of agent-based modeling studies, a key feature of science, to a new level. Using **RNetLogo** in conjunction with tools like **Sweave** (Leisch 2002), **odfWeave** (Kuhn, Weston, Coulter, Lenon, and Otles 2010) or **SWord** (Baier 2009) will contribute to replicability and reproducibility of agent-based simulation studies by automatic and self-documented report generation. For example, **Sweave** can embed R code in a \LaTeX text document. When compiling the **Sweave** document, the R code is evaluated and the results (not only numeric but also images) can be embedded automatically in the \LaTeX document. The **RNetLogo** package opens up the possibility to embed not only results of R, but also the result of a **NetLogo** simulation. We can create a self-documented report with **NetLogo** simulations and R analytics (with or without source code). For an example see the **Sweave** code of this article.

Since models become more complex their computational requirements are increasing as well. A lot of these requirements are compensated by increasing computational power, but the use of modern model development and analysis techniques for stochastic models, like Bayesian calibration methods, make a large number of repeated simulations necessary. Using **RNetLogo** includes, of course, an overhead when converting model results from **NetLogo** to R and vice versa, but there are already techniques available to spread such repetitions to multi-cores and computer clusters (see the **RNetLogo** package vignette “Parallel Processing with **RNetLogo**”). To sum up, I expect that this contribution will make agent-based modeling with **NetLogo** more popular and easier in the R community and will support the methodological developments towards rigorous model development, testing and analysis in the ABM community.

Acknowledgments

I would like to thank two anonymous reviewers as well as Volker Grimm and Winfried Kurth for their very valuable comments on an earlier version of the manuscript.

References

Arifovic J (1994). “Genetic Algorithm Learning and the Cobweb Model.” *Journal of Economic*

- Dynamics and Control*, **18**(1), 3–28.
- Baier T (2009). *SWordInstaller: SWord: Use R in Microsoft Word (Installer)*. R package version 1.0-2, URL <http://CRAN.R-project.org/package=SWordInstaller>.
- Bakshy E, Wilensky U (2007a). *NetLogo-Mathematica Link*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. URL <http://ccl.northwestern.edu/netlogo/mathematica.html>.
- Bakshy E, Wilensky U (2007b). “Turtle Histories and Alternate Universes: Exploratory Modeling with NetLogo and Mathematica.” In M North, C Macal, D Sallach (eds.), *Proceedings of the Agent 2007 Conference on Complex Interaction and Social Emergence*, pp. 147–158. Argonne National Laboratory and Northwestern University.
- Billari FC, Prskawetz A (2003). *Agent-Based Computational Demography: Using Simulation to Improve Our Understanding of Demographic Behaviour*. Contributions to Economics. Physica-Verlag.
- Bowman A, Crawford E, Alexander G, Bowman RW (2007). “**rpanel**: Simple Interactive Controls for R Functions Using the **tcltk** Package.” *Journal of Statistical Software*, **17**(9), 1–23. URL <http://jstatsoft.org/v17/i09/>.
- Carpenter C, Sattenspiel L (2009). “The Design and Use of an Agent-Based Model to Simulate the 1918 Influenza Epidemic at Norway House, Manitoba.” *American Journal of Human Biology*, **21**(3), 290–300.
- Conte R (2006). “From Simulation to Theory (and Backward).” In F Squazzoni (ed.), *Epistemological Aspects of Computer Simulation in the Social Sciences, Second International Workshop, EPOS 2006, Brescia, Italy, October 5–6, 2006, Revised Selected and Invited Papers*, volume 5466 of *Lecture Notes in Computer Science*, pp. 29–47. Springer-Verlag.
- Conte R, Gilbert N, Sichman JS (1998). “MAS and Social Simulation: A Suitable Commitment.” In J Sichman, R Conte, N Gilbert (eds.), *Multi-Agent Systems and Agent-Based Simulation, First International Workshop, MABS ’98, Paris, France, July 4–6, 1998*, volume 1534 of *Lecture Notes in Computer Science*, pp. 1–9. Springer-Verlag.
- Conway J, Eddelbuettel D, Nishiyama T, Sameer KP, Tiffin N (2012). *RPostgreSQL: R Interface to the PostgreSQL Database System*. R package version 0.3-1, URL <http://CRAN.R-project.org/package=RPostgreSQL>.
- Crawley MJ (2005). *Statistics: An Introduction Using R*. John Wiley & Sons.
- Csárdi G, Nepusz T (2006). “The **igraph** Software Package for Complex Network Research.” *InterJournal, Complex Systems*, 1695. URL <http://igraph.sf.net>.
- DeAngelis DL, Mooij WM (2005). “Individual-Based Modeling of Ecological and Evolutionary Processes.” *Annual Review of Ecology, Evolution, and Systematics*, **36**, 147–168.
- Epstein JM, Axtell R (1996). *Growing Artificial Societies: Social Science from the Bottom Up*. The Brookings Institution, Washington, DC.

- Felsen M, Wilensky U (2007). “NetLogo Urban Suite – Sprawl Effect Model.” URL <http://ccl.northwestern.edu/netlogo/models/UrbanSuite-SprawlEffect>.
- Ferrer J, Prats C, López D (2008). “Individual-Based Modelling: An Essential Tool for Microbiology.” *Journal of Biological Physics*, **34**(1–2), 19–37.
- Francois R (2011). “2D Kernel Density Estimator: Perspective Plot and Contour Plot.” URL <http://web.archive.org/web/20120706042750/http://addictedtor.free.fr/graphiques/RGraphGallery.php?graph=1>.
- Gilbert GN (2008). *Agent-Based Models*. Quantitative Applications in the Social Sciences. Sage, Los Angeles, CA.
- Gilbert N (1999). “Simulation: A New Way of Doing Social Science.” *American Behavioral Scientist*, **42**(10), 1485–1487.
- Goedman R, Grothendieck G, Højsgaard S, Pinkus A (2010). *Ryacas: R Interface to the Yacas Computer Algebra System*. R package version 0.2-10, URL <http://CRAN.R-project.org/package=Ryacas>.
- Green S, Hurst L, Nangle B, Cunningham P, Somers F, Evans R (1997). “Software Agents: A Review.” *Technical Report TCD-CS-1997-06*, Trinity College Dublin, Department of Computer Science.
- Griffin AF, Stanish C (2007). “An Agent-Based Model of Prehistoric Settlement Patterns and Political Consolidation in the Lake Titicaca Basin of Peru and Bolivia.” *Structure and Dynamics*, **2**(2), 1–46.
- Grimm V (1999). “Ten Years of Individual-Based Modelling in Ecology: What Have We Learned and What Could We Learn in the Future?” *Ecological Modelling*, **115**(2), 129–148.
- Grimm V, Railsback S (2005). *Individual-Based Modeling and Ecology*. Princeton University Press, Princeton.
- Heckbert S, Baynes T, Reeson A (2010). “Agent-Based Modeling in Ecological Economics.” *The Annals of the New York Academy of Sciences*, **1185**, 39–53.
- Hewitt C (1976). *Viewing Control Structures as Patterns of Passing Messages*. A.I.Memo 410. MIT Press.
- Hipp DR (2012). “About **SQLite**.” URL <http://www.sqlite.org/about.html>.
- Iványi MD, Gulyás L, Bocsi R, Szemes G, Mészáros R (2007). “Model Exploration Module.” In M North, C Macal, C Sallach (eds.), *Proceedings of the Agent 2007 Conference on Complex Interaction and Social Emergence*, pp. 207–215. Argonne National Laboratory and Northwestern University.
- James DA (2011). *RSQLite: SQLite Interface for R*. R package version 0.11.1, URL <http://CRAN.R-project.org/package=RSQLite>.
- James DA, DebRoy S (2012). *RMySQL: R Interface to the MySQL Database*. R package version 0.9-3, URL <http://CRAN.R-project.org/package=RMySQL>.

- Jennings NR (2000). “On Agent-Based Software Engineering.” *Artificial Intelligence*, **117**(2), 277–296.
- Kabacoff R (2010). *R in Action*. Manning.
- Kabacoff RI (2011). *Quick-R: Accessing the Power of R*. URL <http://www.statmethods.net/>.
- Kuhn M, Weston S, Coulter N, Lenon P, Otles Z (2010). *odfWeave: Sweave Processing of Open Document Format (ODF) Files*. R package version 0.7.17, URL <http://CRAN.R-project.org/package=odfWeave>.
- LeBaron B (2000). “Agent-Based Computational Finance: Suggested Readings and Early Research.” *Journal of Economic Dynamics and Control*, **24**(5–7), 679–702.
- Leisch F (2002). “Sweave: Dynamic Generation of Statistical Reports Using Literate Data Analysis.” In W Härdle, B Rönz (eds.), *Compstat 2002 – Proceedings in Computational Statistics*, pp. 575–580. Physica-Verlag.
- Leombruni R, Richiardi M (2004). *Industry and Labor Dynamics: The Agent-Based Computational Economics Approach: Proceedings of the Wild@ace2003 Workshop, Torino, Italy, 3–4 October 2003*. World Scientific.
- Luck M, McBurney P, Preist C (2003). *Agent Technology: Enabling Next Generation Computing (A Roadmap for Agent Based Computing)*. AgentLink, University of Southampton, Southampton.
- Macy MW, Willer R (2002). “From Factors to Actors: Computational Sociology and Agent-Based Modeling.” *Annual Review of Sociology*, **28**, 143–166.
- Maindonald JH (2008). *Using R for Data Analysis and Graphics: Introduction, Code and Commentary*. URL <http://CRAN.R-project.org/doc/contrib/usingR.pdf>.
- Malleson N, Heppenstall A, See L (2010). “Crime Reduction Through Simulation: An Agent-Based Model of Burglary.” *Computers, Environment and Urban Systems*, **34**(3), 236–250.
- Matthews RB, Gilbert NG, Roach A, Polhill JG, Gotts NM (2007). “Agent-Based Land-Use Models: A Review of Applications.” *Landscape Ecology*, **22**(10), 1447–1459.
- Moonen JM (2009). *Multi-Agent Systems for Transportation Planning and Coordination*. ERIM Ph.D. Series Research in Management. Erasmus Research Institute of Management (ERIM), Erasmus University Rotterdam.
- Mukhin D, James DA, Luciani J (2012). *ROracle: OCI Based Oracle Database Interface for R*. R package version 1.1-1, URL <http://CRAN.R-project.org/package=ROracle>.
- North MJ, Collier NT, Vos JR (2006). “Experiences Creating Three Implementations of the Repast Agent Modeling Toolkit.” *ACM Transactions on Modeling and Computer Simulation*, **16**(1), 1–25.
- North MJ, Macal CM, Aubin JS, Thimmapuram P, Bragen MJ, Hahn J, Karr J, Brigham N, Lacy ME, Hampton D (2010). “Multiscale Agent-Based Consumer Market Modeling.” *Complexity*, **15**(5), 37–47.

- Oh R, Sanchez S, Lucas T, Wan H, Nissen M (2009). “Efficient Experimental Design Tools for Exploring Large Simulation Models.” *Computational & Mathematical Organization Theory*, **15**(3), 237–257.
- Oliveira E (1999). “Applications of Intelligent Agent-Based Systems.” In *Proceedings of SBAI – Simpósium Brasileiro de Automação Inteligente*, pp. 51–58. São Paulo.
- Oracle (2013). “Java Native Interface.” URL <http://docs.oracle.com/javase/7/docs/technotes/guides/jni/index.html>.
- Owen WJ (2010). *The R Guide*. URL <http://CRAN.R-project.org/doc/contrib/Owen-TheRGuide.pdf>.
- Pebesma EJ (2004). “Multivariable Geostatistics in S: The **gstat** Package.” *Computers & Geosciences*, **30**(7), 683–691.
- Pebesma EJ, Bivand RS (2005). “Classes and Methods for Spatial Data in R.” *R News*, **5**(2). URL <http://CRAN.R-project.org/doc/Rnews/>.
- Petzoldt T, Rinke K (2007). “**simecol**: An Object-Oriented Framework for Ecological Modeling in R.” *Journal of Statistical Software*, **22**(9), 1–31. URL <http://www.jstatsoft.org/v22/i09>.
- Piacentini M (2012). *SQLite Database Browser*. URL <http://sourceforge.net/projects/sqlitebrowser/>.
- Pinkus A, Winitzki S, Niesen J (2007). *Yacas Computer Algebra System*. URL <http://yacas.sourceforge.net/homepage.html>.
- Railsback SF, Grimm V (2012). *Agent-Based and Individual-Based Modeling: A Practical Introduction*. Princeton University Press.
- R Core Team (2014a). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org>.
- R Core Team (2014b). *R Installation and Administration 3.1.0 (2014-04-10)*. URL <http://CRAN.R-project.org/doc/manuals/R-admin.pdf>.
- R Core Team (2014c). *R Language Definition: Version 3.1.0 (2014-04-10) DRAFT*. URL <http://CRAN.R-project.org/doc/manuals/R-lang.pdf>.
- Reuillon R, Chuffart F, Leclaire M, Faure T, Dumoulin N, Hill D (2010). “Declarative Task Delegation in OpenMOLE.” In W Smari, J McIntire (eds.), *Proceedings of the 2010 International Conference on High Performance Computing and Simulation (HPCS)*, pp. 55–62. Caen, France.
- Ripley B (2012). *RODBC: ODBC Database Access*. R package version 1.3-5, URL <http://CRAN.R-project.org/package=RODBC>.
- RWiki (2006). “**rJava** – R/Java Interface.” URL <http://rwiki.sciviews.org/doku.php?id=packages:cran:rjava>.

- Schelling TC (1969). “Models of Segregation.” *The American Economic Review*, **59**(2), 488–493.
- Shen W, Hao Q, Yoon HJ, Norrie DH (2006). “Applications of Agent-Based Systems in Intelligent Manufacturing: An Updated Review.” *Advanced Engineering Informatics*, **20**(4), 415–431.
- Squazzoni F (2010). “The Impact of Agent-Based Models in the Social Sciences After 15 Years of Incursions.” *History of Economic Ideas*, **XVIII**(2), 197–233.
- Stonedahl F, Wilensky U (2013). “BehaviorSearch.” URL <http://behaviorsearch.org>.
- Sycara KP (1998). “Multiagent Systems.” *AI Magazine*, **19**(2), 79–92.
- Tesfatsion L (2006). “Agent-Based Computational Economics: A Constructive Approach to Economic Theory.” In L Tesfatsion, K Judd (eds.), *Handbook of Computational Economics*, volume 2, chapter 16, pp. 831–880. Elsevier.
- Thiele JC (2014). *RNetLogo: Provides an Interface to the Agent-Based Modelling Platform NetLogo*. R package version 1.0-0, URL <http://CRAN.R-project.org/package=RNetLogo>.
- Thiele JC, Grimm V (2010). “NetLogo Meets R: Linking Agent-Based Models with a Toolbox for Their Analysis.” *Environmental Modelling Software*, **25**(8), 972–974.
- Thiele JC, Kurth W, Grimm V (2011). “Agent- and Individual-Based Modeling with NetLogo: Introduction and New NetLogo Extensions.” In K Römisch, A Nothdurft, U Wunn (eds.), *22. Tagung der Sektion Forstliche Biometrie und Informatik des Deutschen Verbandes Forstlicher Forschungsanstalten und der Arbeitsgemeinschaft Ökologie und Umwelt der Internationalen Biometrischen Gesellschaft – Deutsche Region, 20–21th September 2010 in Göttingen (Germany)*, Die Grüne Reihe, pp. 68–101.
- Tisue S (2012). “Controlling API.” URL <https://github.com/NetLogo/NetLogo/wiki/Controlling-API>.
- Urbanek S (2010). *rJava: Low-Level R to Java Interface*. R package version 0.8-8, URL <http://CRAN.R-project.org/package=rJava>.
- Urbanek S (2011). *RJDBC: Provides Access to Databases Through the JDBC Interface*. R package version 0.2-0, URL <http://CRAN.R-project.org/package=RJDBC>.
- Venables WN, Ripley BD (2002). *Modern Applied Statistics with S*. 4th edition. Springer-Verlag, New York.
- Venables WN, Smith DM, R Core Team (2014). “An Introduction to R.” Notes on R: A Programming Environment for Data Analysis and Graphics, Version 3.1.0 (2014-04-10), URL <http://CRAN.R-project.org/doc/manuals/R-intro.pdf>.
- Weiss G (1999). *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*. MIT Press, Cambridge, MA.
- Wilensky U (1997a). “NetLogo Fire Model.” URL <http://ccl.northwestern.edu/netlogo/models/Fire>.

- Wilensky U (1997b). “NetLogo GasLab Free Gas Model.” URL <http://ccl.northwestern.edu/netlogo/models/GasLabFreeGas>.
- Wilensky U (1998). “NetLogo Virus Model.” URL <http://ccl.northwestern.edu/netlogo/models/Virus>.
- Wilensky U (1999). *NetLogo*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. URL <http://ccl.northwestern.edu/netlogo/>.
- Wilensky U (2012). “**BehaviorSpace**.” URL <http://ccl.northwestern.edu/netlogo/docs/behaviorspace.html>.
- Wilensky U (2013). *NetLogo User Manual, Version 5.0.5*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. URL <http://ccl.northwestern.edu/netlogo/docs/>.
- Wilensky U, Rand W (2014). *An Introduction to Agent-Based Modeling: Modeling Natural, Social and Engineered Complex Systems with NetLogo*. MIT Press. Forthcoming.
- Wooldridge M (2002). *Introduction to Multiagent Systems*. John Wiley & Sons, New York, NY.
- Zuur AF, Ieno EN, Meesters E (2009). *A Beginner’s Guide to R*. useR! Springer-Verlag.

Affiliation:

Jan C. Thiele
Department of Ecoinformatics, Biometrics and Forest Growth
University of Göttingen
Büsgenweg 4
37077 Göttingen, Germany
E-mail: jthiele@gwdg.de
URL: <http://www.uni-goettingen.de/en/72779.html>