An Ecological Model-Based Reasoning Model to Support Nature Park Managers

Mark Hoogendoorn, Jan Treur, and Muhammad Umair

Vrije Universiteit Amsterdam, Department of Artificial Intelligence
De Boelelaan 1081, 1081 HV Amsterdam
Email: {mhoogen, treur, mumair}@few.vu.nl
URL: http://www.cs.vu.nl/~{mhoogen, treur, mumair}

Abstract. A decision support system model is described to advise nature park managers. It applies dynamic modelling techniques to relate abiotic characteristics of a site over time to species that can be found. For a desired vegetation type it determines how such abiotic factors are to be changed in order to obtain the desired change in the vegetation after some time. The system takes into account an ecological model of the temporal dynamics of species, interspecies interactions, and abiotic factors. Applying model-based reasoning and dynamical systems methods to this ecological model, decision options on abiotic conditions are determined in order to obtain desired vegetation types.

1. Introduction

Plants only grow in areas with suitable (abiotic) species-specific environmental conditions. When such abiotic conditions change over time, as a consequence the vegetation of a site may also change. How the occurrence of a species relates to a terrain's abiotic (physical and chemical) characteristics can be expressed as environmental preferences of a species. More specifically, the abiotic preferences of species for factors such as acidity, nutrient value and moisture, are decisive for the question whether or not they can become part of the vegetation on a specific site. The appreciation of a nature park usually lies in the type of flora (and fauna) that can be found. In contrast, measures that can be taken by a manager usually concern the abiotic factors, such as the ground water level. Therefore knowledge about abiotic preferences of plant species, are a crucial element to be used by nature managers in their management. However, nature managers responsible for terrains do not always possess such detailed knowledge, and in particular are not fully aware of how the dynamics of the relationships between abiotic factors and occurrence of species work out over time. Several models have been proposed to represent such relations in a mathematical or logical way (see e.g. [4-9]).This paper describes a decision-support system model that has been designed to support them in their decision making processes. Once an analysis of a terrain has been made, taking into account both the dynamics of abiotic and biotic factors and their interaction, nature managers can use this to manage the terrain, for example by taking measures on abiotic factors to improve the vegetation quality of the site.

The decision-support system model was designed on the basis of temporal dynamical modelling of the dynamics of the abiotic and biotic factors and their relations, and temporal model-based reasoning techniques using the dynamic model. Both a quantitative modelling as well as a qualitative approach are taken, and are applied to a case study within the specified domain. The approaches allow a manager of a nature park to set certain (long term) goals, and can derive using what settings are appropriate to reach these goals.

This paper is organised as follows. In Section 2 the domain of application is treated in more detail. The quantitative and qualitative models are explained in Section 3. Section 4 presents a model-based reasoning approach in order to enable reasoning about the qualitative model (e.g. determine how certain long term ecological gaols can be reached). A mathematical approach to achieve the same is presented in Section 5, and finally, Section 6 concludes the paper.

2. Domain of Application

The domain considered is that of a nature park manager who has to make decisions about his or her terrain. Within such decision processes both abiotic factors and biotic factors play an important role.

Abiotic preferences of a species Every plant species needs a combination of abiotic conditions to grow at a given site: its *abiotic preferences*. For example, the abiotic preferences of *Caltha palustris* L., are: very moist or fairly wet; basic, neutral or slightly acid; nutrient poor, fairly nutrient rich or nutrient rich terrain. For the species *Poa trivialis* L. a terrain needs to be fairly moist, very moist or fairly wet; basic or neutral; nutrient rich or very nutrient rich.

Biotic preferences of a species For a simple approximation the abiotic preferences of a species can be used to determine whether or not a species can grow. However, also interaction between species can play a role, in the sense that the presence of another species may affect a given species in a positive or negative manner: in addition to abiotic preferences, also such *biotic preferences* of species can be used. Some well-known examples of such interactions between two species are:

interaction	**effect of species 2 on species 1**	**effect of species 1 on species 2**
competition	negative	negative
symbiosis	positive	positive
parasitism	positive	negative

Such biotic preferences imply that the suitability of a site does not only depend on the abiotic characteristics of the site and abiotic preferences of species. Dynamic patterns over time may result, such as the periodic predator-prey cyclus as known from the literature. Dynamic modelling methods are required to address such patterns.

Ecological decision making A manager of a nature park has the possibility to manipulate certain factors on the site. Often such factors concern the abiotic circumstances, such as the (ground) water level. However, also the introduction of certain species such as grazers may be included in the set of instruments available to the park manager. This indicates that, in line with what was discussed above, both the dynamics of interactions between species and abiotic factors and the dynamics between different species are to be taken into account within ecological decision making processes. This is the challenge addressed in subsequent sections.

3. An Example Ecological Model

In this section an example ecological model is presented both in qualitative and quantitative format. The model is presented in a simplified form with two competitive species s_1 and s_2 which both depend on the abiotic factor moisture. It is only used for the purpose of illustration. The method presented can be applied to any ecological model. Figure 1 shows a causal diagram for this model. Below, both a qualitative and a quantitative variant of the model are introduced.

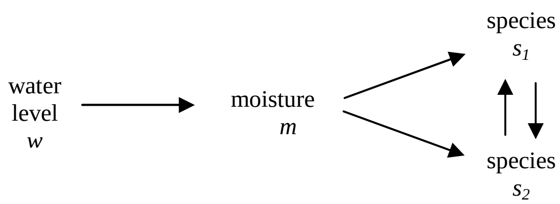

Fig. 1. Causal diagram of ecological model

3.1 Quantitative model

A differential equation form for this model is as follows:

$$d\, s_1(t) / dt \;=\; \beta \; {*}s_1(t) * [c(t) - a_1{*}s_1(t) - a_2{*}s_2(t)]$$
$$d\, s_2(t) / dt \;=\; \gamma{*}s_2(t) * [c(t) - b_1{*}s_1(t) - b_2{*}s_2(t)]$$
$$d\, c(t)/dt \;=\; \omega{*}(\eta\, m(t) \;-\; c(t))$$
$$d\, m(t) /dt \;=\; \Theta * (\lambda\, w - m(t))$$

Here $s_1(t)$ and $s_2(t)$ are the densities of species s_1 and s_2 at time point t; moreover, $c(t)$ denotes the carrying capacity for s_1 and s_2 at t, which depends on the moisture $m(t)$. The moisture depends on the water level indicated by w. This w is considered a parameter that can be controlled by the manager of the terrain, and is kept constant over longer time periods. Moreover the parameters β,γ are growth rates for species s_1, s_2. For carrying capacity and moisture respectively, η and λ are norm proportion parameters, and Θ and ω are speed factors. The parameters a1, a2 and b1, b2 are proportional contribution in the competitive environment for species s1 and s2 respectively. Based on the quantitative model discussed a large number of simulations have been performed resulting in a variety of interesting patterns. An example situation is where the proposed decision support system assists the nature park manager to estimate the densities of species s_1 and s_2 after a certain time (e.g. 10 years) given the current abiotic circumstances (moisture m) that depends on water level w . Figure 2 shows the results for this particular situation.

Note that for this example set of equations, equilibria can be determined as follows:

$\beta * s_1 * [c - a_1 * s_1 - a_2 * s_2] = 0 \qquad \gamma * s_2 * [c - b_1 * s_1 - b_2 * s_2] = 0$

$\eta\, m - c = 0 \qquad \lambda\, w - m = 0$

This can be solved by

$m = \lambda\, w$ and $c = \eta\, m = \eta\lambda\, w$

Moreover,

$s_1 = 0$ or $c - a_1 * s_1 - a_2 * s_2 = 0$ and $s_2 = 0$ or $c - b_1 * s_1 - b_2 * s_2 = 0$

This is equivalent to

Either $s_1 = s_2 = 0$

or $s_1 = c/a_1$ and $s_2 = 0$

or $s_1 = 0$ and $s_2 = c/b_2$

or $s_1 = c\,(a_2 - b_2))/(a_2\, b_1 - a_1\, b_2)$ and $s_2 = -c\,(a_1 - b_1))/(a_2\, b_1 - a_1\, b_2)$

Note that in this simple example model, the equilibria can be determined analytically. However, for the general case it is not assumed that equilibria can be determined in an analytic manner, and it is not assumed that the terrain will reach an equilibrium state within the time period considered.

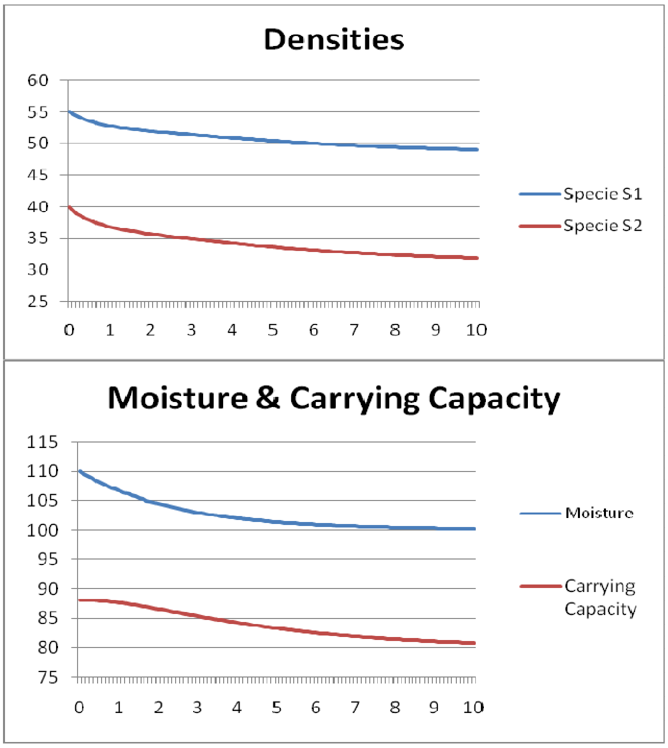

Fig. 2. Predicted densities, moisture and carrying capacity after 10 years (w=200, m(0)=110, c(0)=88, λ=0.5, η=0.8, β=0.01, γ=0.02, Θ=0.4, ω=0.4)

3.2 Qualitative model

Below, a model is introduced whereby a qualitative perspective is taken. Hereby, a number of dependency rules are specified that indicate how the abiotic world and species interact. These dependencies are represented by means of so called leadsto_after rules (cf. [1]). The format of the leadsto_after rule is as follows:

leadsto_after: INFO_ELEMENT x INFO_ELEMENT x DURATION

indicating that from the first information element the second can be derived, whereby the second element becomes true after duration d. The truth of information elements over time is indicated by the at predicate:

at: INFO_ELEMENT x TIME

Which specifies that the information element is true at the given time point. Given these constructs, properties of states can easily be derived. A simple forward reasoning rule is the following:

leadsto_after(I1, I2, D) ∧ at(I1, T) → at(I2, T+D)

More specifics about such reasoning rules are given in Section 4. Below, two variants of a model are specified. One whereby the density of a species depends solely on the abiotic factors, and one which allows for interaction with other species.

Non-interacting species model A simple model whereby the densities of species merely depend upon the moisture level (which in turn is dependent upon the water level) can be represented using the following leadsto_after rules:

leadsto_after(waterlevel(X), moisture(X), 1) where X can e.g. be low, medium or high.

Furthermore, for the dependency between abiotic factors and the density of the population, the following (generic) relationship can be identified:

leadsto_after(and(X, abiotic_preference_for(S, X, pos), has_density(S, D1),
next_higher_density(D1, D2)), has_density(S, D2), 1)
leadsto_after(and(X, abiotic_preference_for(S, X, neg), has_density(S, D1),
next_higher_density(D2, D1)), has_density(S, D2), 1)

Hereby, the preferences can be made explicit, for instance the fact that a particular species prefers high moisture: abiotic_preference_for(species1, moisture(high), pos).

Interacting species model Not having any influence of the different species residing at a particular location is not very realistic. Therefore, the model can be extended to incorporate this factor as well. Hereby, a larger number of leadsto_after rules are required as more complex interactions occur. Two example rules are shown below.

leadsto_after(and(X, abiotic_preference_for(S1, X, pos),
abiotic_preference_for(S2, X, pos), biotic_preference_for(S1, S2, pos),
has_density(S1, D1), next_higher_density(D1, D2)),
has_density(S1, D2), 1)
leadsto_after(and(X, abiotic_preference_for(S1, X, pos),
abiotic_preference_for(S2, X, neg), biotic_preference_for(S1, S2, neg),
has_density(S1, D1), next_higher_density(D1, D2)),
has_density(S1, D2), 1)

Hereby, the abiotic interactions can be set in the same way as specified before, whereas the biotic preferences are explicitly represented, for instance a competition between two species 1 and 2:

biotic_preference_for(species1, species2, neg) biotic_preference_for(species2, species1, neg)

parasitism between species 1 and 2:

biotic_preference_for(species1, species2, pos) biotic_preference_for(species2, species1, neg)

or symbiosis between species 1 and 2:

biotic_preference_for(species1, species2, pos) biotic_preference_for(species2, species1, pos)

4. Decision Support by Model-Based Temporal Reasoning

This section shows how model-based temporal reasoning can be utilized to support nature park managers in reaching the goals they want to set for a certain nature region. The model based-reasoning approach is therefore presented first, after which examples are shown using the qualitative modelling approach. The rules within the reasoning mechanism are specified in an executable logical format called LEADSTO [2]. The basic building blocks of this language are temporal causal relations denoted by $\alpha \twoheadrightarrow_{e, f, g, h} \beta$, which means:

if state property α holds for a certain time interval with duration g,
then after some delay (between e and f) state property β
will hold for a certain time interval of length h.

where α and β are state properties of the form 'conjunction of literals' (where a literal is an atom or the negation of an atom), and e, f, g, h non-negative real numbers. The LEADSTO language features a simulation engine; for more details, see [2].

For both temporal forward and backward simulation well-known reasoning techniques can be applied. An example of a temporal forward reasoning rule is shown below. Hereby a focusing mechanism is used as well, indicating what information elements to focus on. How this focusing mechanism is used is stated in the example case. Note that the subscript below the LEADSTO arrow has been left out, meaning that the standard parameters 0,0,1,1 are used.

P1: Positive forward simulation

If I holds at T and it is known that I leads to J after duration D, and J is in focus, then the J holds after D.

$\forall$I,J:INFO_ELEMENT $\forall$D:DURATION $\forall$T:TIME
at(I, T) $\wedge$ leads_to_after(I, J, D) $\wedge$ in_focus(J) $\twoheadrightarrow$ at(J, T+D)

More forward reasoning rules exist, see [1] for more details. For backward reasoning the abduction principle can be applied:

P2: Positive backward simulation

If it is believed that J holds at T and that I leads to J after duration D, and I is in focus, then it is believed that I holds before duration D.

$\forall$I,J:INFO_ELEMENT $\forall$D:DURATION $\forall$T:TIME
at(J, T) $\wedge$ leads_to_after(I, J, D) $\wedge$ in_focus(I) $\twoheadrightarrow$ at(I, T-D)

The results of applying this rule are not guaranteed to be correct since there could be multiple leads_to_after rules that cause J to occur. Again, see [1] for more details and backward simulation rules.

In the example case, two species of plants are considered s_1 and s_2. The density of the species can have three values: low, medium, and high; for the water level and moisture the same values are allowed. The specific interactions are listed in Table 1.

Table 1. Density change conditions

Preference of s1for abiotic factor	Preference of s2 for abiotic factor	Interaction between s1 and s2	Growth of density of s1
pos	pos	pos	+1
pos	pos	neg	0
pos	neg	pos	0
pos	neg	neg	+1

neg	pos	pos	0
neg	pos	neg	-1
neg	neg	pos	-1
neg	neg	neg	0

For instance, when looking at the first column in the table, in case s_1 has a preference for the current abiotic circumstances, and so does s_2, and they have a positive interaction, then the density of s_1 grows by one as well (e.g. from medium to high). Of course, in case the highest value is reached, the growth no longer occurs. Below, two specific cases are addressed, one for symbiosis between s_1 and s_2, one for a competitive relationship. Note that it is assumed that at least a low population size of each species is present. If also no plants of a species would be taken into account the interaction between the species would become dependent upon the presence of these species. In the quantitative model this information is taken into account.

Symbiosis The first case considered is symbiosis. Hence, the two plants have a positive influence upon each other. Furthermore, both plants prefer medium or high moisture, and dislike low moisture. The manager of the park want to find out what would happen in case he decides to lower the water level in the park. Using forward simulation the proposed support system starts reasoning (given the initial conditions that the current density of both plants is high, and the water level will be low during the coming 5 years). Figure 3 shows the results. Hereby, the left part of the figure denotes the atoms that occur during the simulation run, whereas the right side indicates the simulation time line where a dark box indicates the atom is true at that time point, and a light box indicates false. Note that the arguments in the atoms specify the real world time points derived, which do not have any relationship with the simulation time.

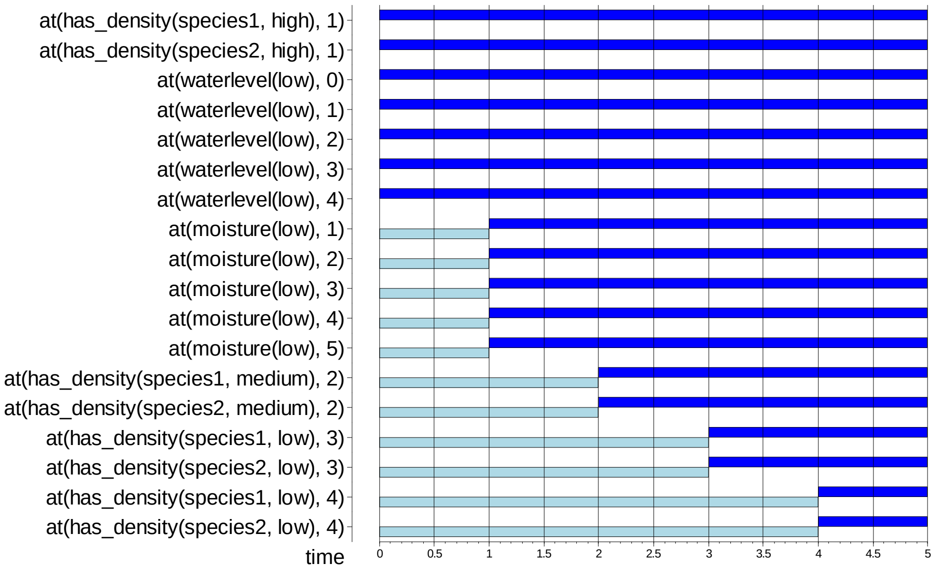

Fig. 3. Forward reasoning for symbiosis case

It can be seen in the trace that at simulation time 1 the predicted moisture levels are calculated, all being low as well:

at(moisture(low, 1)   at(moisture(low, 2)   at(moisture(low, 3)   at(moisture(low, 4)

Furthermore, the densities are calculated. Due to both species disliking the low moisture level, both population densities are predicted to decrease to a medium density within 2 years:

at(has_density(species1, medium), 1) at(has_density(species2, medium), 1)

After that, the densities will even increase to a low level.

Competition In the second case, there are two competitive species, whereby s_2 prefers low moisture, and does not prefer other moisture types, whereas s_1 prefers non-low moisture types. The manager of the nature park wants to establish a high level of s_2, and a low level of s_1, to be established after four years. The manager can ask for advice from the support system, and also has to set a focusing mechanism since the backward reasoning can deliver a lot of results. Therefore, the manager sets a preference for a medium water level, after which a low water level should be considered. In Figure 4 the resulting trace is shown.

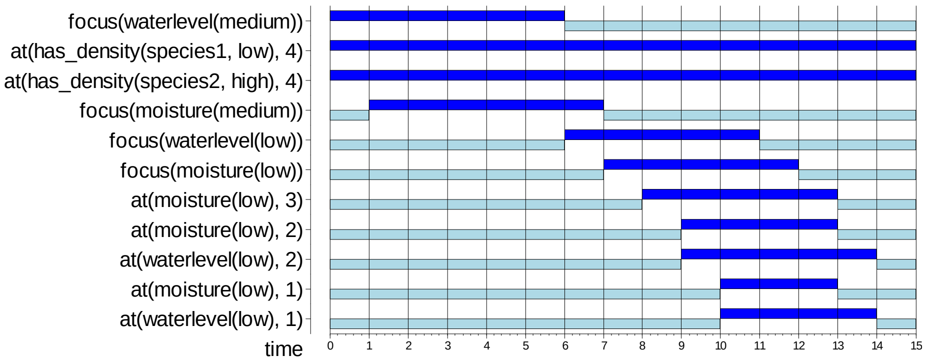

Fig 4. Backward reasoning for competitive case.

It can be seen that the initial goals of the manager are inputted into the system:

at(has_density(species1, low), 4)   at(has_density(species2, high), 4)

Thereafter the reasoning starts (of which only the moisture and water levels are shown for the sake of brevity). The focus is initially set to a medium water level to establish the overall goal: focus(waterlevel(medium)). The backward reason does however not result in possible solutions, therefore the focus is set to a low water level. Here, a solution is indeed found, namely to immediately set the water level to low next year, resulting in the goal being reached.

5. Decision Support by Parameterised Temporal Projection

Differential equations for the sensitivities of values of the variables w.r.t. the parameter *w* are obtained by differentiating the original differential equations for *w*:

$$\partial\ \partial s_1/\partial w/\partial t\ = \beta * \partial s_1(t)/\ \partial w\ [c(t) - a1*s_1(t) - a2*s_2(t)] + \beta * s_1(t) * [\partial c(t)/\ \partial w - a1*\partial s_1(t)/\ \partial w - a2*\partial s_2(t)/\ \partial w]$$

$$\partial\ \partial s_2/\partial w\ /\partial t\ = \gamma * \partial s_2(t)/\ \partial w\ [c(t) - b1*s_1(t) - b2*s_2(t)] + \gamma * s_2(t) * [\partial c(t)/\ \partial w -$$

$b1*\partial s_1(t)/ \partial w$ - $b2*\partial s_2(t)/ \partial w]$

$\partial\, \partial c/\partial w /\partial t \quad = (\eta\, \partial m(t)/ \partial w - \partial c(t)/ \partial w) * \omega$

$\partial\, \partial m/\partial w /\partial t \quad = (\lambda - \partial m(t)/ \partial w) * \Theta$

These equations describe how the values of species s_1, s_2, moisture m and carrying capacity c at time point t are sensitive to the change in the value of the water level parameter w. Figure 2 shows the trend in change of densities of species over 10 years given the initial values of abiotic circumstance (water level w). Using the following formula, the nature park manager can determine the change (Δw) in abiotic circumstance w to achieve the goal at some specific time point in future.

$$\Delta w = [s_1(w+\Delta w) - s_1(w)] / (\partial s_1/\partial w)$$

where $s_1(w+\Delta w)$ is the desired density at time t, $s_1(w)$ the predicted density s_1 at time t for water level w, and $(\partial s_1/\partial w)$ the change in density of s_1 at time t against the change in w. Figure 2 depicts a situation where the densities of species s_1 and s_2 are predicted to decrease, given $w = 200$. Under these settings the density of species s_1 will be *49*. If the nature park manager wants to aim it to become *55* after 10 years, then according to the model described above he or she has to change w to *240* (see Figure 5).

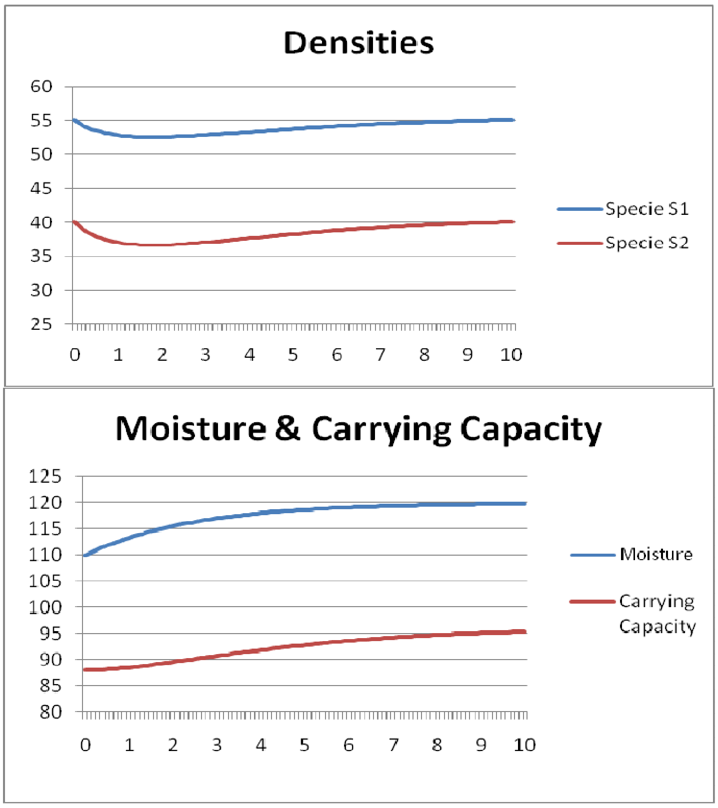

Fig. 5. Densities, moisture and carrying capacity over 10 years, after incorporating $\Delta w = 40$ (w=240, m(0)=110, c(0)=88, λ=0.5, η=0.8, β=0.01, γ=0.02, Θ=0.4, ω=0.4)

6. Conclusions and Related Work

In this paper, an approach has been presented to support managers of nature parks. In order to make this support possible, both a quantitative and qualitative approach have been presented. For both types of models, approaches have been proposed to simulate populations over time as well as setting a certain goal to be reached within a certain period, and deriving how the circumstances can be adjusted to achieve these goals. A qualitative approach has advantages in possibilities for explanation. However, in contrast to qualitative approaches, quantitative approaches cover also cases where only small gradual changes occur that accumulate over time into larger differences. Both approaches have been extensively evaluated using a dedicated case study.

During the last decade, decision support for nature park managers is an area that is addressed more and more, often in combination with GIS-systems; see, for example, [6]. Some of the more known systems proposed are SELES [4] and EMDS [5;7]. Both approaches allow to take into account spatial aspects, which are not addressed yet in the current paper. SELES subsumes aspects of cellular automata, discrete event simulation, and Markov chains, and is primarily based on stochastic Monte Carlo simulations, with fewer possibilities for deterministic models. A difference of the approach put forward in the current paper is that deterministic models are addressed and that both qualitative and quantitative models are supported. EMDS is a mainly qualitative approach and has fewer possibilities to take into account the dynamics of processes over longer time periods. The decision component of EMDS was worked out based on hierarchical multi-criteria decision making. A difference of the approach put forward in the current paper is the emphasis on modelling the dynamics of the processes over time, and the possibility for both qualitative and quantitative models.

Other qualitative models have been proposed as well. Salles *et al.* [9], for example introduce a qualitative model for two interacting species. They form a qualitative theory of these interactions, and implement them within the GARP system [3]. Using this system, a variety of interactions can be simulated using forward simulation. They do however not address the possibility to perform backward reasoning such as addressed in this paper. In [8] another qualitative approach is proposed, modelling more complex interactions between populations in a so-called ant's garden setting. Again, reasoning backward in order to determine how a certain desired state can be reached is not addressed. The authors attempt to run a number of simulations to see whether they result in the appropriate end result.

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