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Modelling the impact of flooding stress on the growth performance of woody species using fuzzy logic

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ABSTRACT

Among the driving processes responsible for riparian forest dynamics the species-specific impact of flooding on the development of woody plants plays a key role—particularly for lowland rivers. Only a few of the forest succession models currently in use incorporate the flooding stress response of trees. This situation is mainly due to the incomplete investigation of the flooding tolerance processes and the related abiotic and biotic factors. In an attempt to use the wide-ranging but still rather vague knowledge available on flooding stress, the research presented in this paper proposes an approach to model tree response to flooding using the fuzzy set theory. The model is illustrated for the case of central European species. Flooding stress response to the abiotic factors of duration, depth and frequency of flooding differs according to five flooding tolerance classes and is expressed by means of a growth factor that limits optimal tree growth. We show that existing fuzzy set theory is able to generate and calibrate a flood stress response model which in turn can be incorporated into more complex forest succession models adapted to riparian areas.

1. Introduction

River management and, in particular, restoration depends on well calibrated modelling approaches that are able to simulate hydraulic regimes, sedimentation, river bed development and vegetation succession. The latter is often mimicked with dynamic vegetation models (see *e.g.*, Bolliger et al., 2000) that are able to simulate the temporal evolution of woody plants under changing environmental conditions. Presently used dynamic vegetation models are biased towards upland conditions and concentrate on characteristics such as temperature stress, nitrogen scarcity or drought stress. One of the few models for riparian conditions is described by Pearlstine et al. (1985). He developed a bottomland hardwood succession model (FORFLO) for studying the impact of an altered hydrologic regime on the growth and succession of coastal forested floodplain in South Carolina, USA. The SWAMP model by Phipps (1979) simulating the forest vegetation dynamics of southern wetlands in Arkansas, USA. Both of these approaches only partially consider the main biotic and abiotic factors implicated in species response to flooding in riparian areas. Moreover, tolerated flood ranges/factors in these models were set on the basis of species response observed at a single river, *i.e.*, the White River (Bedinger, 1971). Apart from these two approaches we found no recent vegetation model that incorporates the impacts of flooding tolerance on the growth of riparian tree species, a stress factor that is extremely important for wetlands (Bedinger, 1971; Siebel and Blom, 1998).

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The lack of modelling tools is not surprising since experimental investigations of flooding tolerance processes and the related abiotic and biotic factors are not systematically done, range from simple qualitative descriptions to quantitative measurements, and are sometimes even contradictory (Glenz et al., 2006). As mentioned by Lexer and Hönninger (2001) this fuzziness of the data quality is due to the difficulty in describing the real system, precisely on account of its complexity.

Stimulated by this knowledge gap and the ability of fuzzy set theory to deal with the described data quality, we aimed at developing a consistent logic to model the species-specific behaviour of woody plants under flooding stress. Thus the main message of the paper is not a methodological one, since we use standard fuzzy logic techniques. We also assemble the wide-ranging but still rather vague knowledge available on flooding stress response and to present the application of the fuzzy set theory to flooding stress modelling. The resulting flooding stress response model (FSR), with a (shoot) growth factor as a target variable, is primarily conceived for integration into more complex forest succession models, such as distribution-based or gap models, which have been adapted to riparian areas.

2. Definition of flooding tolerance

In this research, flooding tolerance is understood as the capacity to survive in anoxic conditions (Hook, 1984) and, hence, flooding stress response is understood as the plant response to submersion. The lack of oxygen affects vital physiological functions and metabolic pathways which can induce various plant responses, including injury, inhibition of seed germination, vegetative and reproductive growth, changes in plant anatomy, promotion of early senescence and mortality. However, the most significant and usual symptom is a decline in shoot growth (Dickson et al., 1965; Kozlowski, 1984; Frye and Grosse, 1992; Ewing, 1996; Blom et al., 1994). Among the driving-processes responsible for riparian forest dynamics, the effect of flooding on tree development plays a key role—particularly in the case of lowland rivers (McKnight et al., 1981). The review by Glenz et al. (2006) suggests that flood tolerance is the expression of the metabolic, physiological, anatomical and morphological adaptations of tree and shrub species to submersion stress, which, on the other hand, is strongly related to non-species-specific abiotic (*e.g.*, flooding depth, duration, frequency, timing of flooding, etc.) and biotic factors (*e.g.*, development stage). Finally, these factors determine the extent of growth reduction or the death of the individual trees considered.

3. Method

The probabilistic treatment of uncertainty is the major field of fuzzy set-based methods (Zimmermann, 1996). The combination of rule-based models and fuzzy logic has proven to be a promising approach to ecological modelling, including population ecology (Bock and Salski, 1998), impact assessment (van der Werf and Zimmer, 1998), and biodiversity research (Kampichler et al., 2000). According to Adriaenssens et al. (2004) the Mamdani–Assilian approach is the generally used design in ecosystem studies. An overview of the various applications of fuzzy logic in environmental modelling is available in two special issues of *Ecological Modelling* (vol. 85, issue 1, *Fuzzy Logic in Ecological Modelling*; vol. 90, issue 2, *Fuzzy Modelling in Ecology*) (Li and Rykiel, 1996; Salski, 1996).

Fuzzy set theory was applied in numerous examples of modelling ecological spatio-temporal processes (*e.g.*, Meesters et al., 1998; Lexer and Hönninger, 2001; Kampichler and Platen, 2004), especially because of its capacity to take the inherent uncertainty of ecological variables into account during inference processing and to express non-linear relations between ecological variables in a transparent way (Adriaenssens et al., 2006).

The theory of the construction of a fuzzy logic control unit (FLC) was described by Lexer and Hönninger (2001) in their application for modelling the effect of site nutrient status on tree growth (PICUS v1.2). Fuzzy logic controllers are systems that use rules instead of algorithms to model knowledge in an explicit manner. Rules link the input variables with the control variable by means of linguistic variables which can be characterized in a simplified form as a quadruple (X, T, U, M). Here, X is the name of the input variable x, T denotes the term set of an input variable x, U is the range of the base variable u which is associated with $T(x)$ via the membership function M, and M defines the degree of membership of each crisp element of U with respect to $T(x)$. For our application we choose the design known as a Mamdani fuzzy controller (Zimmermann, 1996); this design is generally used on ecosystem studies (Adriaenssens et al., 2004).

The input variables are linked with the control variable by the rules of the form:

$$\text{if } x_1 \text{ is } Q_{1j} \text{ and } x_2 \text{ is } Q_{2j} \text{ and } x_3 \text{ is } Q_{3j} \text{ then } y \text{ is } Q_j,$$

where Q_{ij} is the jth term of a linguistic variable X_i and Q_j is the jth term of the control variable. x_i represents the input variables and y the response variable. A set of rules is constructed for each response category. To parameterize, the membership functions $\mu_{ij}(x)$ and $\mu_j(y)$ for each term of the linguistic variables, $x_{\max,i}$ and $x_{\min,i}$ as well as the range where $\mu_{ij}(x) = 1$ were defined by applying the direct rating method (Turksen, 1991). The membership grades of all rule antecedents are aggregated to determine the degree of compatibility, α, using the minimum-operator as a model for the 'and'. The degree of match of each rule is computed as

$$\alpha_r = \min_{i=1,\ldots,n}\{\mu_i^j(x_i^{\text{input}})\}.$$

This concept enables us to obtain the validity of the rule consequences. We assume that rules with a low degree of membership in the antecedent also have little validity and therefore clip the consequence fuzzy sets at the height of the antecedent degree of membership. Formally,

$$\mu_r^{\text{conseq}}(y) = \min\{\alpha_r, \mu^i(y)\}.$$

According to Zimmermann (1996), the combined consequences $\mu^{\text{conseq}}(y)$ from all rules (r) which had been "fired" for a given set of input values were obtained by employing the