A Spatially Explicit Migration Model for Pike

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Abstract. Pike (*Esox lucius* L.) populations have been suffering from habitat degradation and the increasing number of restoration programs had only limited success. In order to set up more effective restoration programmes in the future, it is important to gain insight into the spatio-temporal dynamics of pike. Because no efforts have been spent to develop a spatially explicit model that enables a better understanding of the observed patterns of movement, and actually as a first step towards an integrated spatially explicit model for describing pike dynamics, a model mimicking the movement of pike in the river Yser, Belgium, is proposed.

Keywords: spatially explicit, migration, northern pike, rivers.

1 Introduction

Pike populations have been suffering from the degradation of the environment and, taking into account its role as a top predator and its recreational value, several attempts were undertaken to reintroduce pike in Belgium. However, a rehabilitation was mostly not achieved since the primary causes leading to a relapse of the pike populations, such as poor water quality and habitat deterioration, largely remained. The spatio-temporal distribution of pike in both rivers and still waters was investigated thoroughly throughout the last decade [4], but no efforts have been spent to develop a spatially explicit model for gaining better understanding of the observed patterns of movement. The use of spatially explicit models in ecology is manifold and their contribution to a full understanding of the spatio-temporal dynamics has long been considered promising [6].

Motivated by the lack of a spatially explicit model for describing the movement of pike, we propose a model to mimic the spatial distribution of pike within one of Belgium's principal rivers, namely the river Yser. The actual study area covers a 10 km stretch of the river and contains three artificial spawning grounds. This stretch was conveniently represented by a rectangular region in which the position of the individuals could be identified unambiguously by means of a Cartesian

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coordinate system centered halfway the river at the downstream boundary of the study area. As a means to quantify the habitat suitability, a map of the habitat suitability index (HSI) was composed [5] based upon a survey of the vegetation type and the naturalness of the bank reinforcements [1].

2 Model Development

2.1 Equations of Motion

Basically, the spatio-temporal dynamics of a pike individual i is governed by a vector equation that was proposed originally to simulate the motion of interacting particles in a plane [7]. This vector equation allows to describe the position $p_i(t) = (x_i(t), y_i(t))$ of the i-th pike that belongs to a population of size N through time and is given by

$$\mathbf{x}_i(t + \Delta t) = \mathbf{x}_i(t) + v_i(t)\,\frac{\mathbf{W}_i(t)}{\|\mathbf{W}_i(t)\|}\,\Delta t\,, \tag{1}$$

where $\mathbf{x}_i(t) = [x_i(t), y_i(t)]^{\mathrm{T}}$ (the location) and $v_i(t)$ is the swimming speed of the i-th individual. Further, $\mathbf{W}_i(t)$ is a weighted average, *i.e.*

$$\mathbf{W}_i(t) = \big(1 - \alpha_i(t)\big)\,\mathbf{P}_i(t) + \alpha_i(t)\,\mathbf{Q}_i(t)\,, \tag{2}$$

of two unit vectors $\mathbf{P}_i$ and $\mathbf{Q}_i$ that steer the direction in which pike i moves depending on the presence of other individuals in its neighborhood and the season ($\mathbf{P}_i$), and the attraction to spawning grounds ($\mathbf{Q}_i$). The swimming direction θ_i of a given pike i, which is defined by the angle between the horizontal axis of an orthogonal coordinate system centered in $(x_i(t), y_i(t))$ and the vector of motion, can be obtained from

$$\begin{bmatrix}\cos\theta_i(t)\\ \sin\theta_i(t)\end{bmatrix} = \frac{\mathbf{W}_i(t)}{\|\mathbf{W}_i(t)\|}\,. \tag{3}$$

Essentially, the weighing coefficient $\alpha_i(t)$ in Eq. (2) allows to alter the relative contribution of $\mathbf{P}_i(t)$ and $\mathbf{Q}_i(t)$ in the determination of $\mathbf{W}_i(t)$. Hence, it enables a periodization of the individuals' behaviour through time. Yet, the formulation of the unit vectors $\mathbf{P}_i(t)$ and $\mathbf{Q}_i(t)$ has to be modified in order to mimic the behaviour of pike.

2.2 Seasonal Behaviour

Three periods during which pike show distinct migratory behaviour are distinguished in one annual cycle. A spawning season (February 15 - May 15) with long distance migration [3], a passive sedentary period that runs from the end of the spawning season until the start of the winter (December 1) with long stationary periods, interchanged with short-lasting movements to catch their preys [4] and finally, an active sedentary season that differs from the passive one as the individuals have to look for their potential preys more actively [4].

Fuzzy sets are used to make a distinction between the different behavioural periods. The weighing function $\alpha_i(t)$ in Eq. (2) can be contemplated as a trapezoidal fuzzy set with parameters $(45, 73, 104, 134)$ to distinguish between the spawning and the sedentary period, where it should be noticed that the first of January is labeled as day number one. Similarly to the weighing function $\alpha_i(t)$, a weighing function $\beta_i(t)$ that grasps the transition between periods in which pike individuals display distinct degrees of activity can be defined as a trapezoidal fuzzy set with parameters $(104, 104, 304, 334)$ [4].

2.3 Swimming Direction

The swimming direction is determined by the unit vectors $\mathbf{P}_i(t)$ and $\mathbf{Q}_i(t)$. The first vector $\mathbf{P}_i(t)$ embodies the direction outside the spawning period and is defined as

$$\mathbf{P}_i(t) = \begin{bmatrix} \cos\varphi_i(t) \\ \sin\varphi_i(t) \end{bmatrix} . \tag{4}$$

Since numerous papers report that pike exhibit territorial behaviour outside the spawning period [2,3,4], every individual i is assigned a circular territory that is centered at $c_i = (x_i^\tau, y_i^\tau)$, has radius r_i, and through which pike i can swim freely. During the passive sedentary season r_i is set to 50 m. On the other hand, preliminary findings in the framework of an ongoing telemetry study have shown a considerably larger home range during the active sedentary season, namely $r_i = 2000$ m.

Taking this and the behaviour of pike into consideration, $\varphi_i(t)$ in Eq. (4) is a β-weighted sum of the behaviour during the passive sedentary season and the one during the active sedentary season. The behaviour during the passive sedentary season is defined in such a way that a pike i flees in the direction of its territory center if it encounters a congener or crosses the outskirts of its territory ($r_i = 50$ m). During the active sedentary season, pike i only flees if it crosses the outskirts of its territory ($r_i = 2000$ m) seen the absence of cannibalism.

2.4 Swimming Speed

On the basis of preliminary findings in the framework of an ongoing telemetry study, the swimming speed, expressed in meter per day, of every individual i was supposed to be distributed normally, *i.e.* $N(1230, 650)$. Yet, in order to account for discrepancies that have been observed between the degrees of activity during different seasons [4], both $\alpha_i(t)$ and $\beta_i(t)$ are used to stipulate that the mean swimming speed during the spawning season is 1230 m day^{-1}, whereas it is supposed to be only 1230/3 m day^{-1} during the active sedentary season [4]. Further, since it is to be expected that pike are even less active during the passive sedentary season, a mean swimming speed of 123 m day^{-1} is assumed.

3 Simulation Results

We chose $\Delta t = 3600$ s and reflecting boundaries. Initially, each of the 50 pikes are assigned a territory that is located within the concerned river stretch. These

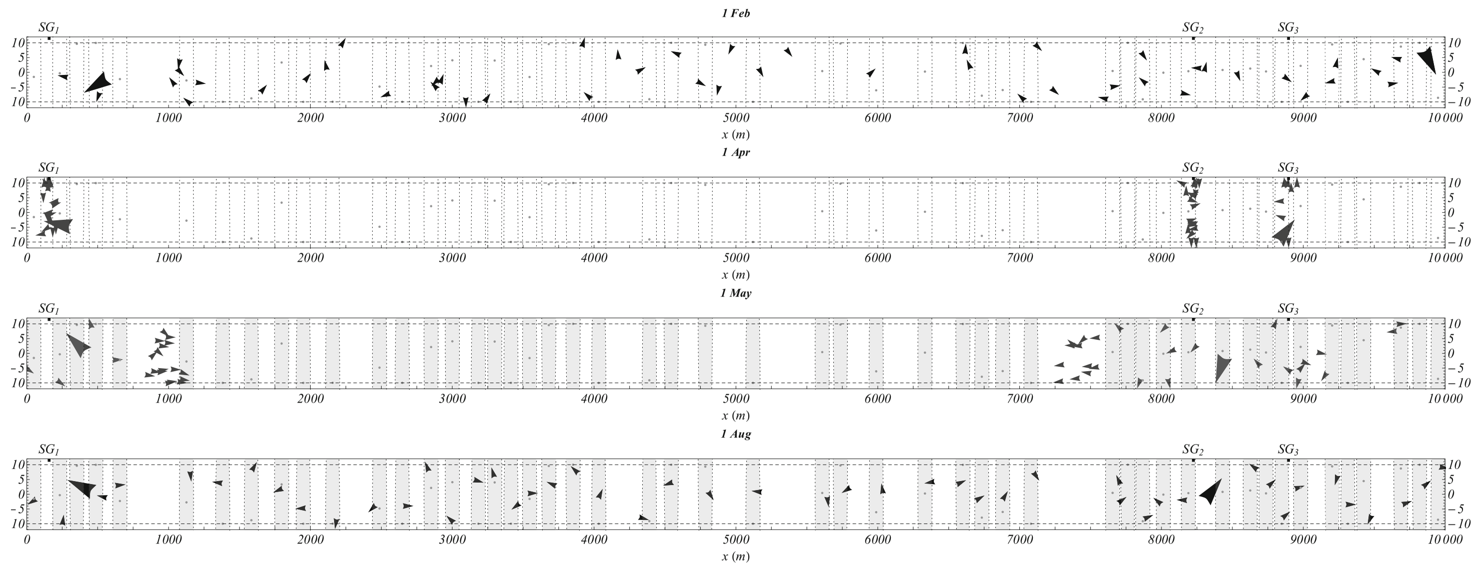

Fig. 1. Simulated spatial distribution of the individuals (arrowheads) within the study area at the beginning of four different days during an annual cycle together with the territories (dotted lines) determined by minimization of the overlap between its own territory and the one of individuals in its vicinity and the maximazation of the habitat HSI. They are colored gray with an opacity proportional to beta (if homing is important, the territories are colored). The individuals, of which two are shown by large arrowheads for tracking purposes, are represented by black arrowheads if $\alpha_i(t) = 0$ (outside the spawning season) and gray arrowheads if $\alpha_i(t) > 0$ (during the spawning season). The spawning grounds are indicated as SG_k.

territories cannot be randomly distributed across the river stretch, but it is natural to assume that a pike individual will try to minimize the overlap between its own territory and the one of individuals in its vicinity because it is a solitary and cannibalistic species [2], while, at the same time, it will try to maximize the suitability (HSI) of its habitat.

Figure 1 shows just one possible realization of the annual cycle and depicts snapshots of the simulated spatial pike distribution within the study area at the beginning of four different days during an annual cycle. The dates at which snapshots are shown, were selected such that the movement patterns during both the sedentary and spawning season can be inferred. From the first snapshot it is obvious that all members of the population are residing within their large territory ($r_i = 2000$ m) prior to the start of the spawning season, whereas on March 1, pike are colored gray and have migrated towards the spawning grounds. By the first of May the spawning season has finished, pike become territorial and return to their territories ($r_i = 50$ m) where they can be retrieved from the summer on.

4 Conclusions

The developed spatially explicit model allows for mimicing the seasonal behaviour of pike. Even though it is presented in the framework of attempts for understanding the spatio-temporal dynamics of pike in the river Yser, it is generic in the sense that it can be tuned easily if another fish species or other regions is at stake by tuning its parameters using species-specific data.

References

1. Bry, C.: Role of vegetation in the life cycle of pike. Pike: Biology and Exploitation, pp. 45–68. Chapman and Hall, Londen (1996)
2. Craig, J.F.: Pike biology and exploitation. Chapman and Hall, Londen (1996)
3. Harvey, B.: A Biological Synopsis of Northern Pike (*Esox lucius*). Canadian Manuscript Report of Fisheries and Aquatic Sciences 2885 (2009)
4. Koed, A., Balleby, K., Mejlhede, P., Aarestrup, K.: Annual movement of adult pike (*Esox lucius* L.) in a lowland river. Ecol. Freshw. Fish 15, 191–199 (2006)
5. US Fish and Wildlife Service: Standards for the development of habitat suitability index models. Tech. rep., US Fish and Wildlife Service (1981)
6. Van Winkle, W., Rose, K.A., Chambers, R.C.: Individual-based apporach to fish population dynamics: an overview. Trans. Am. Fish. Soc. 122, 397–403 (1993)
7. Vicsek, T., Czirok, A., Ben-Jacob, E., Cohen, I., Shochet, O.: Novel type of phase transition in a system of self-driven particles. Phys. Rev. Lett. 75, 1226–1229 (1995)