LimnoSES - social-ecological lake management undergoing regime shifts

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Abstract

LimnoSES is a coupled system dynamics, agent-based model to simulate social-ecological feedbacks in lake use and management. The focus lies on shallow lakes where ecological regime shifts can occur between the turbid and the clear water state. We provide a regime shift evaluation tool which considers social responses and regulation mechanisms of nutrient inflow to the lake. In particular, the coordination among private house owners with insufficient sewage water systems and the regulating municipality play an important role since it causes time lags of social responses to changes in the lake state.

1 Overview

1.1 I.i.a What is the purpose of the study?

The main purpose of the model is to simulate social-ecological feedbacks in lake use and management where ecological regime shifts can occur between the turbid and the clear water state. We further extend traditional regime shift evaluations with an investigation of transient dynamics from social responses and regulations affecting the nutrient load to the lake. In particular, the issues of cooperation between different interest groups and time lags of social responses to changes of the lake state play an important role.

1.2 I.i.b For whom is the model designed?

For scientists of different disciplinary backgrounds who contribute to research on lake management and look for a deeper understanding of the interplay between social and ecological dynamics.

1.3 I.ii.a What kinds of entities are in the model?

The model consists of a social and an ecological submodel. The following descriptions describe both submodels separately (see for an graphical overview Figure 1). Ecological entities: The ecological submodel represents the lake that

*https://www.comses.net/codebases/5292/releases/1.1.0/

includes the stocks for a predator and a prey fish species (pike – Esox Lucius and bream – Abramis brama respectively). The density of macrophytes is estimated as a function from bream. Social entities: One agent represents the municipality and its function to regulate sewage treatment and potentially enforce the upgrade of sewage treatment systems from private house owners. Hundred agents represent private house owners that release nutrients to the lake and decide on potential upgrade of their sewage treatment system.

1.4 I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?

Ecological entities: The two fish species are represented as stock densities and characterized by growth, mortality and interaction rates. (see for details and numbers section III.iv.b) Social entities: The municipalities legislation activity can be triggered by monitoring that the pike density drops below a threshold. The house owners have an onsite sewage system (OSS) that can be upgraded. House owners are characterized by a willingness-to-upgrade that can be increased by information through neighbors who upgraded their sewage system ('social engagement') or through regular checks by the municipality ('central enforcement').

1.5 I.ii.c What are the exogenous factors/drivers of the model?

Ecological submodel: The food web in the lake is driven by the amount of nutrients which can be a time series for nutrient increase/decrease scenarios. In the coupled model, the amount of nutrients is subject to the number of households that release insufficiently treated sewage water into the lake. Social submodel: The abundance of nutrients is monitored by the municipality to estimate the necessity to regulate private sewage treatment. Different nutrient levels are assumed in the scenarios to trigger regulation and inform the private house owners about the need to upgrade their sewage system.

1.6 I.ii.d If applicable, how is space included in the model?

Not included within functions. Lake and land area are only visualized on the simulation platform.

1.7 I.ii.e What are the temporal and spatial resolutions and extents of the model?

The ecological submodel runs on daily time steps, the social submodel on annual time steps. Thus, the processes of monitoring/legislation and house owner decisions about upgrading the private sewage system are made once per year.

1.8 I.iii.a What entity does what, and in what order?

1. **Pollution:** House owners release nutrients through their OSS and in case they were informed about the need to upgrade the OSS, they decide

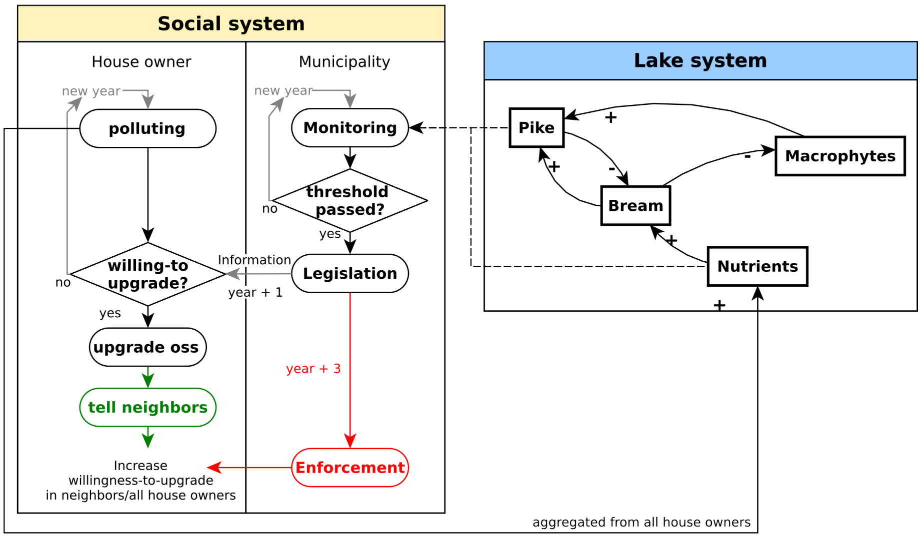

Figure 1: Process overview on the agent-based social model and the system dynamics based ecological model.

whether to do this investment (can be done only once). If house owners upgrade their OSS in the 'social pressure' scenario, they also inform their neighbors about the modernization which increases their neighbors' willingness to upgrade.

2. **Ecosystem dynamics:** Nutrients affect the system dynamics of lake: fish (bream and pike) and macrophytes.

3. **Regulation:** The Municipality evaluates monitoring results and starts the legislation for private sewage treatment when the triggering nutrient level is passed. As a consequence, house owners are informed about the new law and the need to modernize their OSS. For the 'central enforcement' scenario, municipal inspectors are sent out to check on the installed OSS and to motivate house owners which increases their willingness to upgrade.

2 Design concepts

2.1 Theoretical and empirical background

2.1.1 II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?

The model addresses social-ecological interactions and therefore includes a social and an ecological submodel that describe the specific subsystem characteristics. The main interactions are monitoring of the lake's state and potential pollution of the lake by applying insufficient sewage treatment installations. Further interactions are foreseen for upcoming versions, as for example biomanipulation or the use of multiple ecosystem services. The ecological submodel is a reimplementation of a minimum model that enables regime shifts between the clear and the turbid state of the lake (Scheffer, 1989). The social submodel is based on assumptions on social norms that in some situations might overwrite the purely economic reasons for a certain behavior. The case is in general informed by current lake management practices in Sweden and regulation of on-site sewage (OSS) treatment systems (Wallin et al., 2013b).

2.1.2 II.i.b On what assumptions is/are the agents' decision model(s) based?

The municipalities decision on regulating private sewage treatment is based on nuntrient levels which are assumed to trigger regulation. Triggering nutrient levels can be classified as pro-active (with values below 2.1, which is the critical nutrient value or tipping point), intermediate (around 2.5) and late (3.0) (see section). House owners agents are assumed to take individual decisions when requested to upgrade their sewage system. They find themselves in a high-cost low-benefit situation (Wallin et al., 2013a) and tend to avoid timely upgrade of their OSS (expressed by the variable willingness-to-upgrade).

2.1.3 II.i.c Why is/are certain decision model(s) chosen?

Due to a lack of empirical evidence, only the simplest assumptions are used here: a probability called willingness-to-upgrade that determines when house owners upgrade their OSS.

2.1.4 II.i.d If the model/submodel (e.g. the decision model) is based on empirical data, where do the data come from?

Not applicable yet.

2.1.5 II.i.e At which level of aggregation were the data available?

Not applicable.

2.2 Individual decision making

2.2.1 II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?

Subjects are individual house owner agents.

2.2.2 II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?

Not applicable.

2.2.3 II.ii.c How do agents make their decisions?

Decision making is triggered by the information about sewage regulations from the municipality. Then current value for the willingness-to-upgrade is the probability with which they decide about the OSS update.

2.2.4 II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?

The willingness-to-update can be changing through interventions, either through horizontal information from neighbors that recently updated their OSS or vertical through the municipality that sends out inspectors to check for the current state of the installed OSS. In both scenarios, the willingness-to-upgrade is increased by 50% but it cannot exceed 1.

2.2.5 II.ii.e Do social norms or cultural values play a role in the decision-making process?

In the 'central enforcement' scenario, inspectors are sent out by municipalities to check the current installation of private sewage systems. Based on empirical studies (Wallin et al. 2013), we can assume that house owners want to follow the rules (represented by increase of their willingness-to-upgrade).

2.2.6 II.ii.f Do spatial aspects play a role in the decision process?

No

2.2.7 II.ii.g Do temporal aspects play a role in the decision process?

Yes, the willingness-to-upgrade is increased either through stochastic interaction with neighbors or by central enforcement (inspector checks) from the municipality. So, with increasing values for the willingness-to-upgrade, the probability for upgrades increases over the course of one simulation.

2.2.8 II.ii.h To which extent and how is uncertainty included in the agents' decision rules?

Not applicable.

2.3 Learning

2.3.1 II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?

Not applicable.

2.3.2 II.iii.b Is collective learning implemented in the model?

Not applicable.

2.4 Individual sensing

2.4.1 II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?

Not applicable.

2.4.2 II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?

Not applicable.

2.4.3 II.iv.c What is the spatial scale of sensing?

Not applicable.

2.4.4 II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?

The municipality receives annual updates on the current nutrient content in the lake, it does not read daily variations.

2.4.5 II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?

No.

2.5 Individual prediction

2.5.1 II.v.a Which data do the agents use to predict future conditions?

Not applicable.

2.5.2 II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?

Not applicable.

2.5.3 II.v.c Might agents be erroneous in the prediction process, and how is it implemented?

Not applicable.

2.6 Interaction

2.6.1 II.vi.a Are interactions among agents and entities assumed as direct or indirect?

In the scenario of 'social engagement', the horizontal information exchange about OSS update is considered to be direct.

2.6.2 II.vi.b On what do the interactions depend?

On the spatial distance, we assumed a neighborhood radius of three units.

2.6.3 II.vi.c If the interactions involve communication, how are such communications represented?

No communication is modelled.

2.6.4 II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?

Not applicable.

2.7 Collectives

2.7.1 II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?

No

2.7.2 II.vii.b How are collectives represented?

Not relevant

2.8 Heterogeneity

2.8.1 II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?

The willingness-to-upgrade can vary during the 'social engagement' scenario.

2.8.2 II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?

No.

2.9 Stochasticity

2.9.1 II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?

The geographical location and therewith the neighborhood from individual agents is initialized randomly. For doing the OSS upgrade, individual agents have an individual probability whether they do the upgrade.

2.10 Observation (incl. emergence)

2.10.1 II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?

Not applicable.

2.10.2 II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)

The aggregated pollution from private house owners is calculated from the number of not-updated OSS which updates the nutrient level for each simulated year (Fig 2). Further for each simulation, the following time lags are recorded:

- **Ecological lag 1:** Years between nutrient concentration transgressing the tipping point (2.1) and pike levels dropping below 1.5 (below initial level).
- **Ecological lag 2:** Years between nutrient concentration transgressing the tipping point towards the clear state (0.9) and pike levels returning to a level above 1.5. (= lake recovery)
- **Policy lag:** Years between the critical nutrient level (2.1) transgressed and municipality initiating regulation. Can be pro-active (at nutrient load 2.0), intermediate (2.5) or late (3.0).
- **Implementation lag:** Years between municipalities regulation and 95% of house owners completing the OSS upgrade.
- **Social response lag:** Policy lag + implementation lag.
- **Nutrient restoration time:** Years between nutrient concentration transgressing the tipping point towards the turbid state (2.1) and turning back to clear state (0.9).
- **Ecological response lag:** Years between house owners completing the upgrade until pike levels return to levels above 1.5.
- **Pike restoration time:** Years between pike levels dropping below 1.5 (below initial level) and returning to levels above 1.5.
- **Lake restoration time:** Years between nutrient concentration transgressing the tipping point and pike levels return to levels above 1.5.

3 Details

3.1 Implementation details

3.1.1 III.i.a How has the model been implemented?

The ecological submodel was first implemented in Matlab Grind to identify suitable value ranges for the alternative stable states. The coupled model was then implemented in NetLogo 6.0.1 where the ecological submodel was reproduced

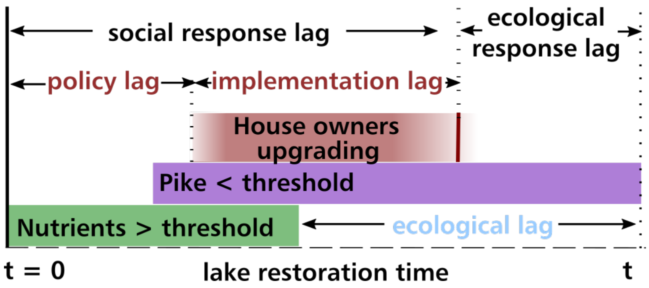

Figure 2: Periods from transient dynamics in LimnoSES which determine important social and ecological time lags.

within the system dynamics editor. The social submodel was implemented with the common NetLogo interface.

3.1.2 III.i.b Is the model accessible, and if so where?

LimnoSES is published through openabm.org (https://www.comses.net/codebases/5292/releases/1.1.0/) and a review process of the documentation and the code (Rollins et al. 2014) is requested. Most recent model versions are available under https://bitbucket.org/seslink/limnoses.

3.2 Initialization

3.2.1 III.ii.a) What is the initial state of the model world, i.e. at time t = 0 of a simulation run? b) Is the initialization always the same, or is it allowed to vary among simulations? c) Are the initial values chosen arbitrarily or based on data?

For the ecological submodel test, we initialized the lake variables either for the turbid or the clear state:

Table 1: Initial setting

State	Nutrients	Pike $[gm^{-2}]$	Bream $[gm^{-2}]$
Clear	0.7	2.6	25.8
turbid	2.5	0.04	84

Values stem from two independent implementations, one in Matlab where we identified stable states numerically and one from a reimplementation NetLogo.

3.3 Input

3.3.1 III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?

No

3.4 Submodels

3.4.1 III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?

1. House owners release nutrients
Assumptions for a total number of households (h) that may contribute to eutrophication of the lake through untreated sewage leaking into the catchment:

- A minimum threshold of polluting households is tolerated (tl) that does not lead to increases in nutrients in the lake.
- The number of $affectors$ above this threshold tl translates linearly into an amount of sewage-water with a maximum value 0.1.
- If less than the threshold tl is polluting, the difference is contributing in the same way (linearly) to reduction of nutrients until the initial nutrient level is reached. This means that at a tl of 50% and 80% of households upgraded the OSS, 30% of the maximal change value of nutrients is applied to reduce the current nutrient level in the lake. Tolerance values lower than 50% would indicate that a slower maximum decrease in nutrients is possible than increases.

The change of the annual nutrient load from sewage is given by:

$$f(affectors) = -\frac{tl \cdot sewage_{max}}{h - tl} + \frac{sewage_{max}}{h - tl} \cdot affectors \tag{1}$$

Parameter	comment	Value [per year]
$sewage_{max}$		0.1
tl	Tolerance level of polluting households	50 [%]
h	Total number of households	100

2. System dynamics at the lake
For the concentration of bream:

$$\frac{dbream}{dt} = im + r \cdot \frac{nutr}{nutr + H_1} \cdot bream - cb \cdot bream^2 - \frac{bream^2}{bream^2 + H_4^2} \cdot pike \cdot predation_{rate} \tag{2}$$

For the concentration of pike:

$$\frac{dpike}{dt} = im + pike \cdot predation_{rate} \cdot predation_{efficiency} \cdot \frac{bream^2}{bream^2 + H_4^2} \cdot \frac{V}{V + H_2} - pike \cdot mortality - cp \cdot pike^2 \tag{3}$$

With V being the dependent proportion of macrophyte vegetation in the lake:

$$V = K \frac{H_3^2}{H_3^2 + bream^2} \tag{4}$$

3. Municipality regulation

- 0) baseline: immediate response to pike threshold means that houseowners are directly informed and they have a uniformly distributed willingness-to-upgrade

- a) ‘central enforcement’: we assume centralized, regular monitoring activities of the lake water quality. When it is perceived as necessary, new rules are developed, such as “Lex Ringsjön”. This asks houseowners to install particular private sewage systems and they are regularly checked whether their installation works sufficiently or not. So all houseowners receive the information about the new law at the same time but their compliance rate is low.
- b) ‘social engagement’: individual houseowners perceive the state of the lake through swimming or fishing activities. Since they are educated, they also see the necessity to upgrade their sewage system but this ’mind shift’ may happen at certain events and not for all houseowner at once. But as soon as they see their neighbor doing it, the compliance rate is high.

3.4.2 III.iv.b What are the model parameters, their dimensions and reference values?

The ecological parameters are taken from the original minimal model from Scheffer (1989), (Tab. 2).

Table 2: Ecological parameters and values from an ecological minimal model (Scheffer 1989)

Parameter	**comment**	**Value** [*daily*]
r_{bream}		$7.5 \cdot 10^{-3} day^{-1}$
$predation_{rate}$	maximum predation rate of pike	$prmax : 0.05 day^{-1}$
$predation_{efficiency}$	pike conversion efficiency to growth	0.1
Mortality pike		$2.25 \cdot 10^{-3} day^{-1}$
cb [cp]	Intraspecific competition constant for bream [pike]	$7.5 \cdot 10^{-5} m^2 g^{-1} day^{-1} [2.75 \cdot 10^{-4} day^{-1}]$
im_x	Immigration rates for fish	$2 \cdot 10^{-5} gm^{-2} day^{-1}$
K	Maximum capacity for vegetation to cover the lake	100 %
	Half saturation constants on how	
H1	- nutrients supports bream growing	0.5 (dimension less)
H2	- vegetation supports pike reproduction	10 %
H3	- bream disturbs vegetation	$20 g/m^2$
H4	- pike predates on bream which supports pike growth	$15 g/m^2$

3.4.3 III.iv.c How were the submodels designed or chosen, and how were they parameterized and then tested?

The following tasks were performed:

1. Find out whether submodels exhibit multiple stable states, determine initial conditions that lead to stable state
2. Check: How do parameter changes affect equilibrium? Which parameters allow for large or only small changes while keeping the characteristics of the system?
3. Extend this test to include social processes, variables.

Table 3: Implemented experiments in the NetLogo BehaviorSpace to test and validate model assumptions, analyze the sensitivity of patterns towards input variation, and to explore model behavior in extended experiments.

Test or experiment	Hypothesis and assumptions	Observed effects	Follow up question
I: “Rtipping” – Transient nutrient in-/decrease	Hysteresis	Sudden shifts in bream and pike abundance appear, but it is dependent on the rate of nutrient change.	Why is the rate only affecting eutrophication and not restoration?
II: “TurbidityResponse” a) start with turbid state	Social pressure between house-owners works faster than top-down rule enforcement	Yes, but only in conditions were the initial willingness-to-upgrade is greater than 0.2	In what way would results differ in a fully coupled system?
III: “Full-Restoration”	Social response lags may cause even larger lags in restoring the pike level	Pike restoration time increases non-linearly with the social time lag	Where does the variability between runs originate from?

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