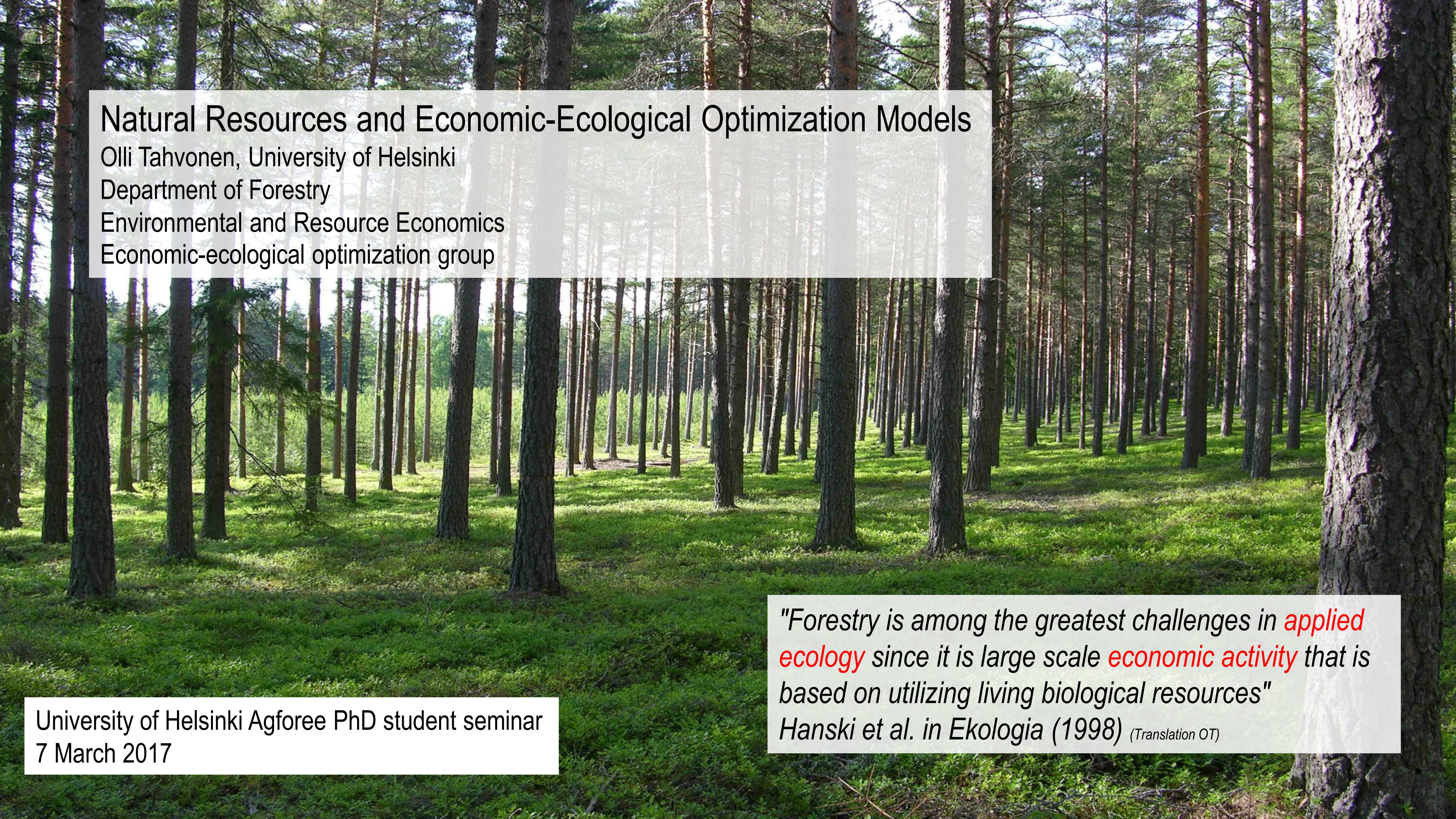


Natural Resources and Economic-Ecological Optimization Models

Olli Tahvonen, University of Helsinki
Department of Forestry
Environmental and Resource Economics
Economic-ecological optimization group

"Forestry is among the greatest challenges in applied ecology since it is large scale economic activity that is based on utilizing living biological resources"
Hanski et al. in Ekologia (1998) *(Translation OT)*

University of Helsinki Agforee PhD student seminar
7 March 2017

“A man who’s handprint can be seen everywhere”

- Danish **Jan Geld** graduated in architecture 1960
- His education was based on strict modernistic approach where e.g. traffic strongly determines city planning
- Then Jan met a charming Danish girl Ingrid who studied psychology and who asked a provoking question: “Why architects find bricks more interesting than humans”?
- The rest is history: Geld is now world famous and has been “Making Cities for People” from Moscow to Tokyo and New York


A 18 HELSINGIN SANOMAT TORSTAINA 23.2.2017

KAUPUNKI

Kaupunkisuunnittelu: Arkkitehti Jan Gehlin kiinnostus siirtyi tiilistä ihmiseen, kun hän tapasi psykologivaimonsa

Mies, jonka kädenjälki näkyy kaikkialla

Miksi Helsingissäkin puuhataan kävelykatuja ja autoja ajetaan ahtaalle? Ainakin yksi syypää on tanskalainen Jan Gehl.

Lari Malmberg HS

Helsingin keskustan Ateneuminkuja toteuttaa Jan Gehlin ajatuksia hyvästä kaupungista.

Jan Gehl haluaisi, että kaupungit olisivat enemmän kävelijöitä hellivän Venetsian kaltaisia.

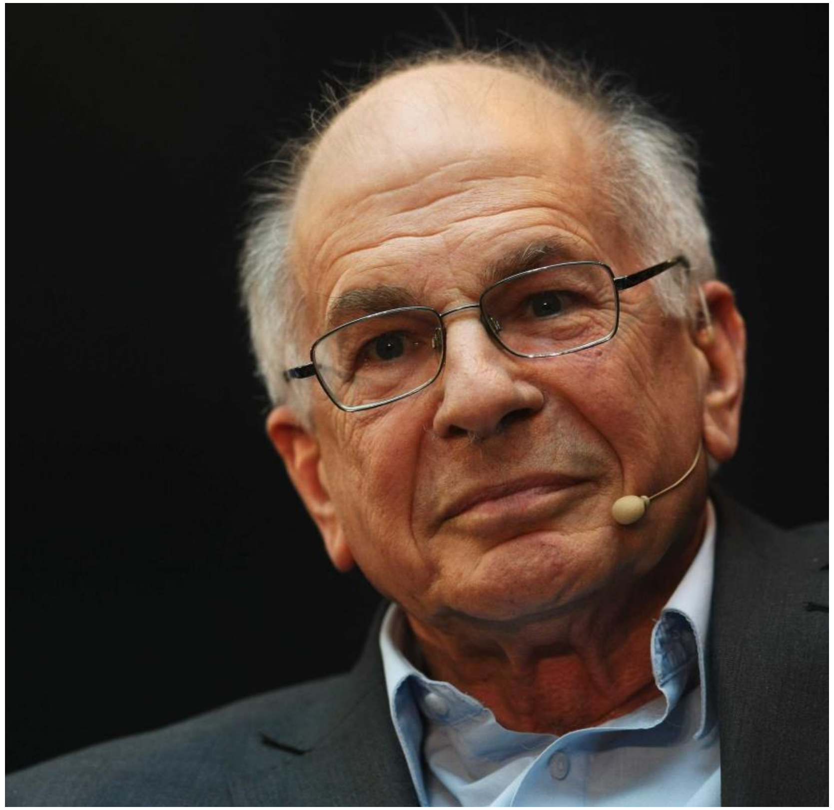
Itäkeskuksen Prisman ympäristö edustaa kaupunkisuunnittelua, joka tuskin miellyttäisi Gehliä.

"Autot olivat hyvä keksintö villiin länteen, mutta huono kaupunkiin."

Jan Gehl

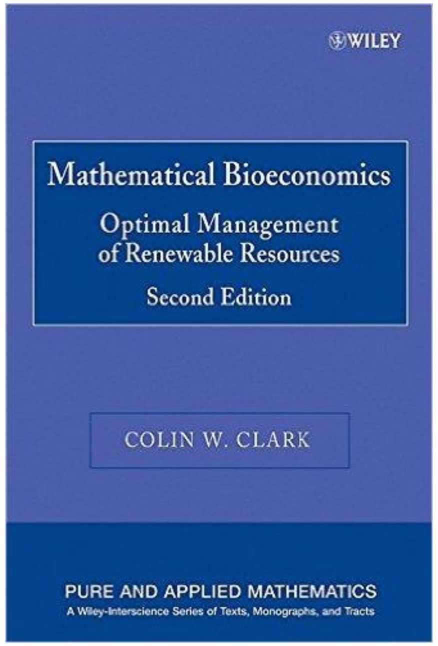
Daniel Kahneman (1934-), an Israeli-American psychologists

- Studied psychology and mathematics
- Kahneman has changed the understanding of economic decision making as a psychologists
- His research has changed the picture on human rationality
- Nobel Memorial Prize in Economic Science 2002
- *The Economist* has listed him among the ten most influential living economists in the world



Colin W. Clark (1931-), a Canadian mathematician, University of British Columbia

- Clark’s research has shown how to integrate economics, ecology and mathematics for understanding the management of renewable resources
- Clark’s studies and classic book “Mathematical Bioeconomics” have influenced the direction for research on the economics of renewable natural resources over last 40 years
- His research has promoted the worldwide implementation of the individual fisherman quota system in fishery management



Content

What kind of ecological models are suitable to be integrated with economics?

1. On economic-ecology interdisciplinarity
2. Model coupling methodology
3. Optimization/economics vs. scenario analysis/ecologists
4. Five examples on economic-ecological optimization setups
   Forestry, reindeer and fisheries
5. Some common problems in economics-ecology model coupling
6. Summary

"Forestry is among the greatest challenges in applied ecology since it is large scale economic activity that is based on utilizing living biological resources" Hanski et al. in Ekologia (1998) *(Translation OT)*

The textbook assumes that the economic objective in forestry is MSY (maximum sustainable yield in m^3)
However, MSY is not a sensible economic objective for renewable resources
E.g. in forestry MSY does not explain timber harvesting decisions and it yields economic losses
=>Should studies on forestry take economic objectives of forestry as they are understood in (forest) economics?

Similar question for economists:
In economics production is a process where factors of production are combined to produce valuable output
=>Should economic studies on production with biological or ecological bases take the description of these processes as they are understood in biology or ecology?

My answer is positive to both of these questions =>*interdisciplinary* research on renewable resources
One possibility for interdisciplinary research: *model coupling methodology*

Model coupling –methodology in resource economics*

Three type of models in resource economics:

1: Generic "simple" models
- Solved by analytical methods
- Give basic understanding on economic trade offs, etc
- Not useful in "practice", "unrealistic assumptions"

2: Generic models with economic extensions
- Typically still solved by analytical methods
- Ecology still "oversimplified" but economics may be complex

3: Detailed empirical models
- Solved numerically
- Economic parts of the models are still in line with economic theory
- Ecological/biological parts represent realistic models taken directly from ecology/biology

=>model coupling methodology

* Model Coupling in Resource Economics: Conditions for Effective Interdisciplinary Collaboration

Miles MacLeod and Michiru Nagatsu*

In this article we argue for the importance of studying interdisciplinary collaborations by focusing on the role that good choice and design of model-building frameworks and strategies can play overcoming the inherent difficulties of collaborative research. We provide an empirical study of particular collaborations between economists and ecologists in resource economics. We discuss various features of how models are put together for interdisciplinary collaboration in these cases and show how the use of a coupled-model framework in this case to coordinate and combine background models from ecology and economics provided particular collaborative affordances and clear collaborative gain.

1. Introduction. Recent years have seen a burgeoning interest in promoting and analyzing interdisciplinary collaboration in the natural and social sciences by researchers and university administrators. There is now a substantial collection of academic work and policy documents available on the subject. Most interdisciplinarity research so far has been the domain of science policy and science and technology studies. This research has focused on the institutional, organizational, and social dimensions of scientific research that promote or inhibit interdisciplinary interactions while developing policy frameworks and guidelines for structuring scientific institutions and organization to promote interdisciplinary interactions (see, e.g., Gibbons et al. 1994). What is largely missing however is an actual case-based study of how the available cognitive resources of different scientific fields and disciplines—their extant theories, modeling templates, experimental and evi-

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*To contact the authors, please write to: Miles MacLeod, Cubicus Building, Dienerlolaan 5, Enschede 7522 NB, Netherlands; e-mail: m.a.j.macleod@utwente.nl.

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Natural resources as dynamical systems with state variables and control variables

Many natural resources can be described as systems of state $\mathbf{x}_t=(x_1,x_2,\ldots,x_n)$
and control variables $\mathbf{u}_t=(u_1,u_2,\ldots,u_n)$:

$$
\begin{aligned}
x_{1,t+1} &= f_1\left(x_{1t},x_{2t},\ldots,x_{nt},u_{1t},u_{2t},\ldots,u_{mt},t\right),\\
x_{2,t+1} &= f_2\left(x_{1t},x_{2t},\ldots,x_{nt},u_{1t},u_{2t},\ldots,u_{mt},t\right),\\
&\cdots\\
x_{n,t+1} &= f_n\left(x_{1t},x_{2t},\ldots,x_{nt},u_{1t},u_{2t},\ldots,u_{mt},t\right),
\end{aligned}
\tag{1}
$$

$$x_{i0} = \tilde{x}_i,\ i=1,\ldots,n,\ t=0,\ldots .$$

- The vector of state variables may describe the state of a forest, the state of forest soil, the state of atmosphere etc
- The vector of control variables may describe the number of harvested trees, emissions, artificial regeneration, etc
- The values of control variables can be directly determined by human decisions
- The development of the state variables can be influenced via the control variables (sometimes directly)

In applied ecological (or closely related) research

- The control variables may not exist (e.g. development of a natural forest)
- Or they may follow some scenario (silvicultural instructions, BAU emissions)
- The model outcomes are described by applying some finite set of scenarios
- The understanding obtained may be used to produce policy and management advices

In economic research

- *An objective function* specifies the economic outcome of resource management and the task is to find an optimal solution trajectory for the control variables that maximizes this outcome, i.e. the problem is to

$$\max_{\{\mathbf{u}_t, t\in[0,\infty)\}} \sum_{t=0}^{\infty} U(\mathbf{x}_t, \mathbf{u}_t, t)$$

subject to the ecological model (1) and some nonnegativity conditions for $\mathbf{x}_t$ and $\mathbf{u}_t$.

Why optimization is important in economics?

- Optimization is an accurate and powerful method to analyse the economic structure and trade-offs of a given problem
- It is very natural to ask what management choices yield highest long term economic benefit from natural resources
- In descriptive analysis it is important to know the outcome if firms attempt to maximize profits, consumers their “utility”, and resource owners (land, forest) their discounted income (e.g. is the outcome sustainable?)

=>the approach yields testable hypothesis on the behavior of natural resource owners, resource markets, etc

=>the approach yields supply and demand, market prices, and understanding how market failures should be corrected by taxes, emission trading, subsidies, legislation, etc

Comparing the ecological and economic approaches

- Ecologists: economists are forced to simplify ecological models to be able to apply optimization
  Comment: Partly true, models cannot include everything
- Ecologists sometimes have distrust of economic concepts like profit, interest rate, efficiency, markets,… (Beacon et al 2008)
  Comment: Please, wake up

- From the economic point of view computing the ecological model assuming some scenarios is not enough to show that the ecological model works
- Deriving management advices is problematic without explicit specification of some theoretical sound management objective
- The management advices derived are partial: it is restrictive to consider the effect of rotation period on carbon storage without considering thinnings and the number of planted seedlings simultaneously

Examples of studies applying the economic-ecological model coupling methodology and the problems faced

Example 1: forestry

Scand. J. For. Res. 17: 274–288, 2002

Taylor & Francis
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Economics of Forest Thinnings and Rotation Periods for Finnish Conifer Cultures

KARI HYYTIÄINEN and OLLI TAHVONEN
Finnish Forest Research Institute, Unioninkatu 40A, FI-00170 Helsinki, Finland

Scandinavian Journal of Forest Research

Hyytiäinen, K. and Tahvonen, O. (Finnish Forest Research Institute, Unioninkatu 40A, FI-00170 Helsinki, Finland). *Economics of forest thinnings and rotation periods for Finnish conifer cultures*. Received April 6, 2001. Accepted November 13, 2001. Scand. J. For. Res. 17: 274–288, 2002.

In this study simultaneous optimization of thinnings and clear-cutting was investigated. The density-dependent whole-stand model was specified for all relevant Finnish Norway spruce [*Picea abies* (L.) Karst.] and Scots pine (*Pinus sylvestris* L.) site indices and solved by non-linear programming. Sensitivity analysis showed that in some cases and owing to endogenous thinnings the optimal rotation length may increase with the rate of interest and site fertility, and decrease with harvesting cost. The number of thinnings is more sensitive to changes in the rate of interest, logging conditions and site productivity for Scots pine stands than for Norway spruce stands. Economic optimization suggests that for both species the first thinning should be performed later than officially recommended. The last thinning should be heavier than officially recommended, especially at high rates of interest. This increases the optimal rotation length compared with solutions under restricted thinning intensity. *Key words: optimal rotation, optimal thinnings, Picea abies, Pinus sylvestris, rate of interest.*

Correspondence to: K. Hyytiäinen, e-mail: kari.hyytiainen@metla.fi

INTRODUCTION

Thinning is perhaps the most important intermediate activity in even-aged forest management. From the economic point of view it leads to earlier harvesting revenues and increases the value growth of residual trees. In Finland, about 20% of the domestic timber supply comes from thinnings (Anon. 1993).

The economic theory of timber production is well established (Faustmann 1849, Preßler 1860, Ohlin 1921, Samuelson 1976). However, most economic research on stand-level forest management ignores thinnings. It is through the use of density-free whole-stand growth models that most of the knowledge has been obtained about how the optimal rotation length and long-term timber supply depend on economic parameters such as prices, costs, rates of interest and taxes (see e.g. Chang 1983, 1984, 1998, Johansson & Lõfgren 1985, Montgomery & Adams 1995). Such models are also suitable for adding various economic complexities (e.g. Willasen 1998, Tahvonen et al. 2001). However, it is an open question whether the results are robust when any of the intermediate forestry activities are included in the analysis.

Simultaneous determination of interacting thinnings and rotation period is a complex problem. The problem was at first specified as a continuous-time optimal control problem (e.g. Näslund 1969, Schreuder 1971). Clark (1976), Clark & De Pree (1979), Cawrse et al. (1984) and Betters et al. (1991) showed that the optimal solution for thinning is a singular path with a time period where thinning is applied continuously. This theoretical model is intuitively appealing, but the drawback is that thinning forests continuously is unrealistic.

Optimization models with detailed empirical growth specifications are often too complex to be solved analytically. Numerical methods have been used to solve whole-stand models (e.g. Kilkki & Väisänen 1969, Brodie et al. 1978) and increasingly complex individual-tree (e.g. Roise 1986, Valsta 1992), distance-dependent (e.g. Pukkala et al. 1998*b*, Vettenranta & Miina 1999) and stage-structured growth models (e.g. Haight 1987, Solberg & Haight 1991). Increasing the complexity may have improved the reliability of the results, but it has forced researchers to concentrate heavily on numerical solution techniques. Typically, the optimization results are given only for one or a few parameter values, which is not enough for determining the rich relationships between optimal forest management and various economic and biological factors.

Recent Finnish studies on optimal timber management use highly advanced descriptions of growth (e.g. Valsta 1992, Miina 1996, Pukkala et al. 1998*b*, Vettenranta & Miina 1999). These and earlier studies do not, however, explain exhaustively how the char-

The setup:

- A mathematical model by Vuokila and Väliaho (1980) was used to specify Norway spruce and Scots pine stand growth
- Optimization method: Matlab optimization algorithms
- Economic outcome of forest management is maximized by the choice of thinning intensity and timing and the rotation period

Results:

- a unified picture on optimal thinning and rotation periods for Norway spruce and Scots pine
- Rotation periods in silvicitural instructions are long

=>this causes economic losses for forest owners and the economy as a whole

Problems in the growth and yield model:

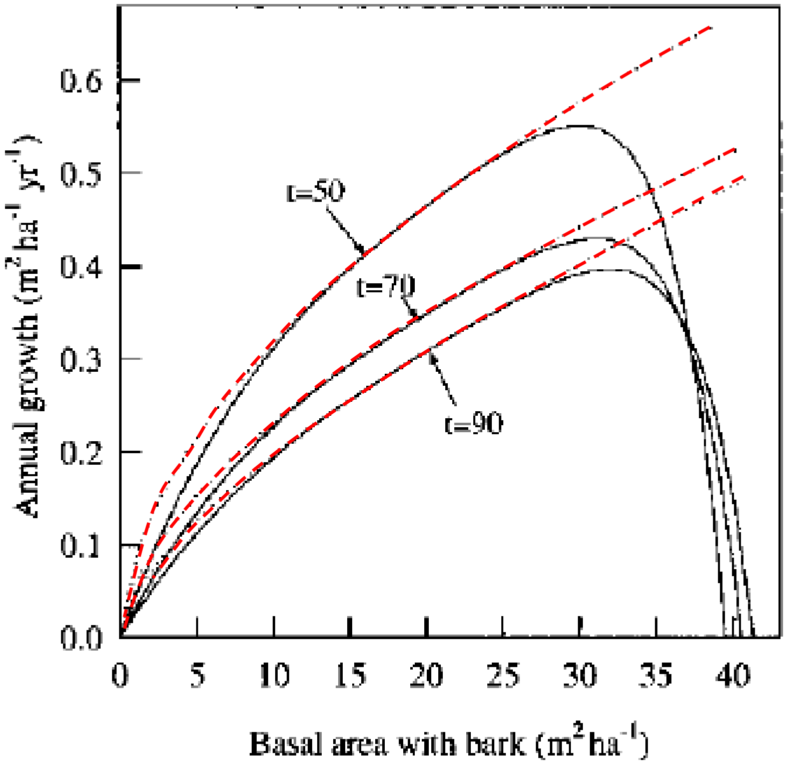


Fig. 1. Annual growth in basal area with bark in a typical Scots pine site, $H(100) = 24$. Solid lines represent modified growth equations and dotted lines the original equations by Vuokila & Väliaho (1980).

1. The Vuokila-Väliaho model does not include reasonable "density dependence"
   =>unbounded stand growth is possible and becomes "optimal"

- This is not revealed if the model is computed assuming conventional management scenarios
- It was necessary to fix the model and add density dependence using knowledge from other studies

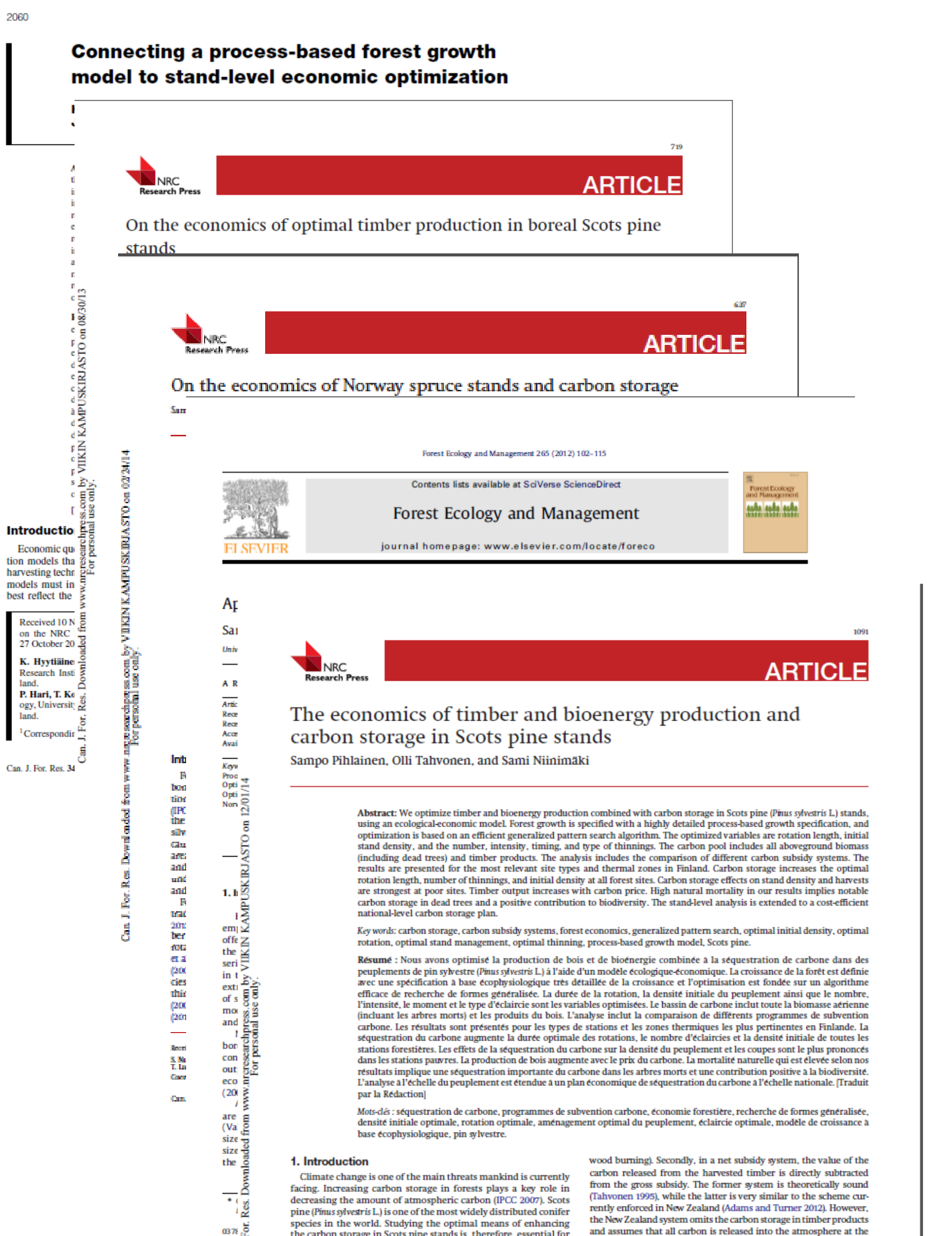
2. With high discount rate (>5%) the optimal rotation became infinitely long and stand density very low

- Reasons: no natural regeneration in the ecological model
  not possible to optimize the regeneration investment

Comments obtained from ecologists:

- Vuokila-Väliaho model is statistical-empirical model and may not describe the ecological causal relationships correctly

Example 2: forestry



The setup

- Forest growth: a detailed process based ecological model (by A. Mäkelä)
- 5 timber assortments, detailed harvesting cost model,…
- Economic objective: timber production, carbon sequestration
- With and without climate change
- Matlab pattern search algorithm used in optimization

Results:

- The process based model is suitable for optimization
- Detailed picture on the economics of timber production, carbon storage,…
- Finnish silvicultural instructions and legislation have caused economic losses
- Under climate change optimal adaptation is important
- The model was used to redesign Finnish silvicultural recommendations

Problems, comments

- In the beginning optimization found results that were invalid
  =>it was necessary to modify the ecological model with the ecologist
- The ecological model did not yet include natural regeneration
- Economists: “your model is too complicated”
  Our reply: timber quality important, causality important
- Some foresters: “The empirical basis of process based models is weak,…”
  Our reply: these models may work in the future climate

Example 3: forestry

The setup

- Developing a forest economic model without any preconditions on forest management system (even/uneven-aged forestry)
- Growth models: Bollandsås et al (2008), Pukkala et al. (2009,…2013)
- Optimization: a mixed integer optimal control problem with state variables up to 40
- Bollandsås et al. model works well without harvesting and with optimization (only infinite yield in m^3 and negative diameter growth)

Results

- Theoretically sound economic approach to continuous cover forestry (CCF) with results on optimal harvest timing, intensity etc
- Optimized CCF does not yield an economic disaster, quite the contrary

Problems

- Are the available ecological models valid?
- Not enough models “outside the box”
- With multiple tree species computation is close to the computation limits

=>parallel computing with supercomputers

Criticism obtained: still under demand

Mixed forest example: Norway spruce, birch and Scots pine

$$J(\chi, T) = \max_{\{h_{st}, \delta_t, T \in [t_1, \infty)\}} \frac{-w + \sum_{t=t_1}^{T-1} \left[\sum_{i=1}^{3} R(\mathbf{h}_{it}) - C_{ith}(\mathbf{h}_{it}) - \delta_t C_f \right] b^{\Delta(t+1)} + \left[\sum_{i=1}^{3} R(\mathbf{h}_{iT}) - \hat{C}_{cl}(\mathbf{h}_{iT}) - \delta_T C_T \right] b^{\Delta(T+1)}}{1 - b^{\Delta(T+1)}} \quad (1)$$

Economic objective function

subject to,

$$x_{i1,t+1} = \phi_i(\mathbf{x}_t) + [1 - \alpha_{i1}(\mathbf{x}_t) - \mu_1(\mathbf{x}_t)] x_{i1t} - h_{i1t}, \; t = t_1, \ldots, T, \; i = 1,2,3, \quad (2)$$

$$x_{is+1,t+1} = \alpha_{is}(\mathbf{x}_t) x_{ist} + [1 - \alpha_{is+1}(\mathbf{x}_t) - \mu_{is+1}(\mathbf{x}_t)] x_{is+1,t} - h_{is+1,t}, \; i = 1,2,3, \; s = 1, \ldots, n-1, \; t = t_1, \ldots, T, \quad (3)$$

Size-structured transition matrix model (e.g Bolandsås et al 2008)

$$h_{ist} = \delta_t h_{ist}, \; \delta_t : Z \in [0,1], \; t = t_0, t_0 + 1, \ldots i = 1,2,3, \; s = 1, \ldots, n, \quad (4)$$

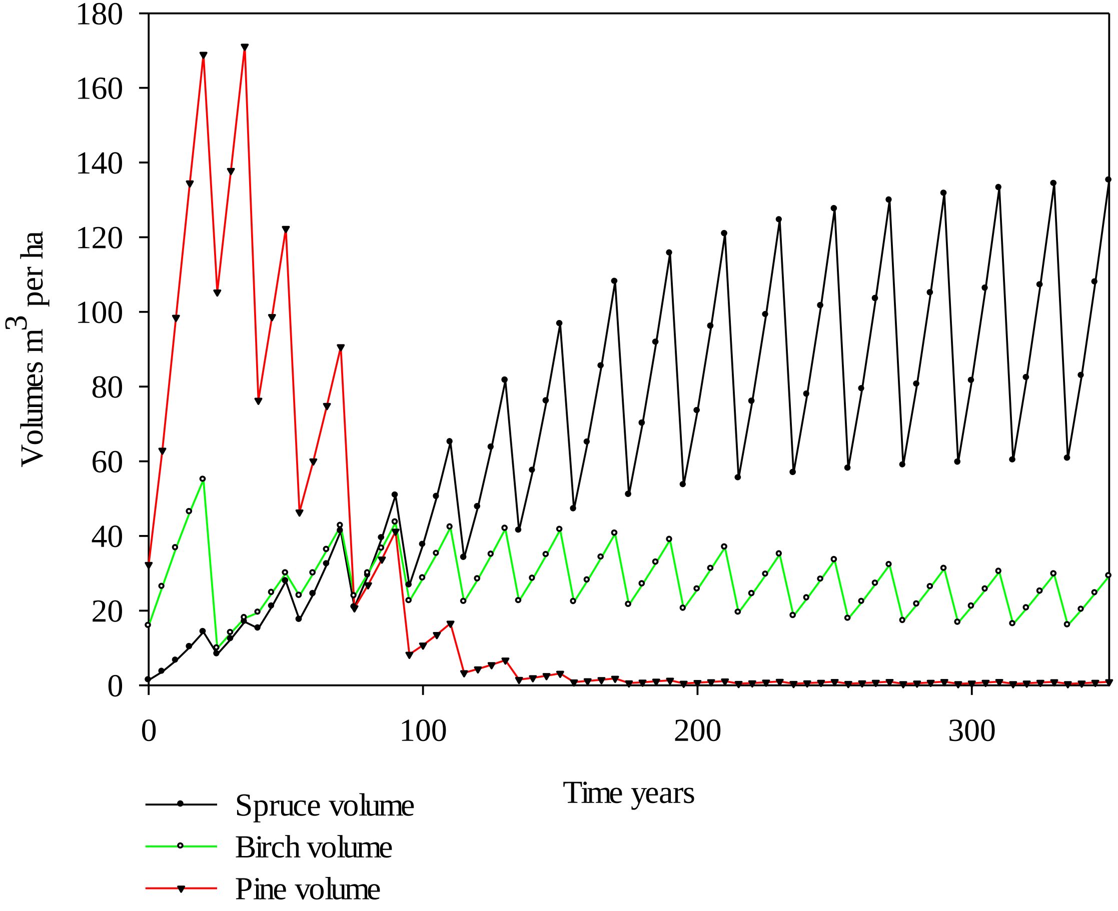
Harvest timing

$$x_{i1t_1} = \chi, \; x_{ist_1} = 0, \; i = 1,2,3, \; s = 2, \ldots, n, \quad (5)$$

Note:
Each species have their own growth, harvesting cost etc models

Tahvonen and Rämö 2017

Example: stand artificially regenerated for Scots pine but long run optimal solution is a naturally regenerating CCF Norway spruce, Scots pine and birch mixture



Site fertility: good (SI=17), interest rate 3%

Initial state: Norway spruce 100, Birch 1000, Pine 1750 (number of trees, in smallest size class)

Optimal harvesting interval: 15-20 years

All harvests: optimal to thin from above

Diameter of harvested trees:

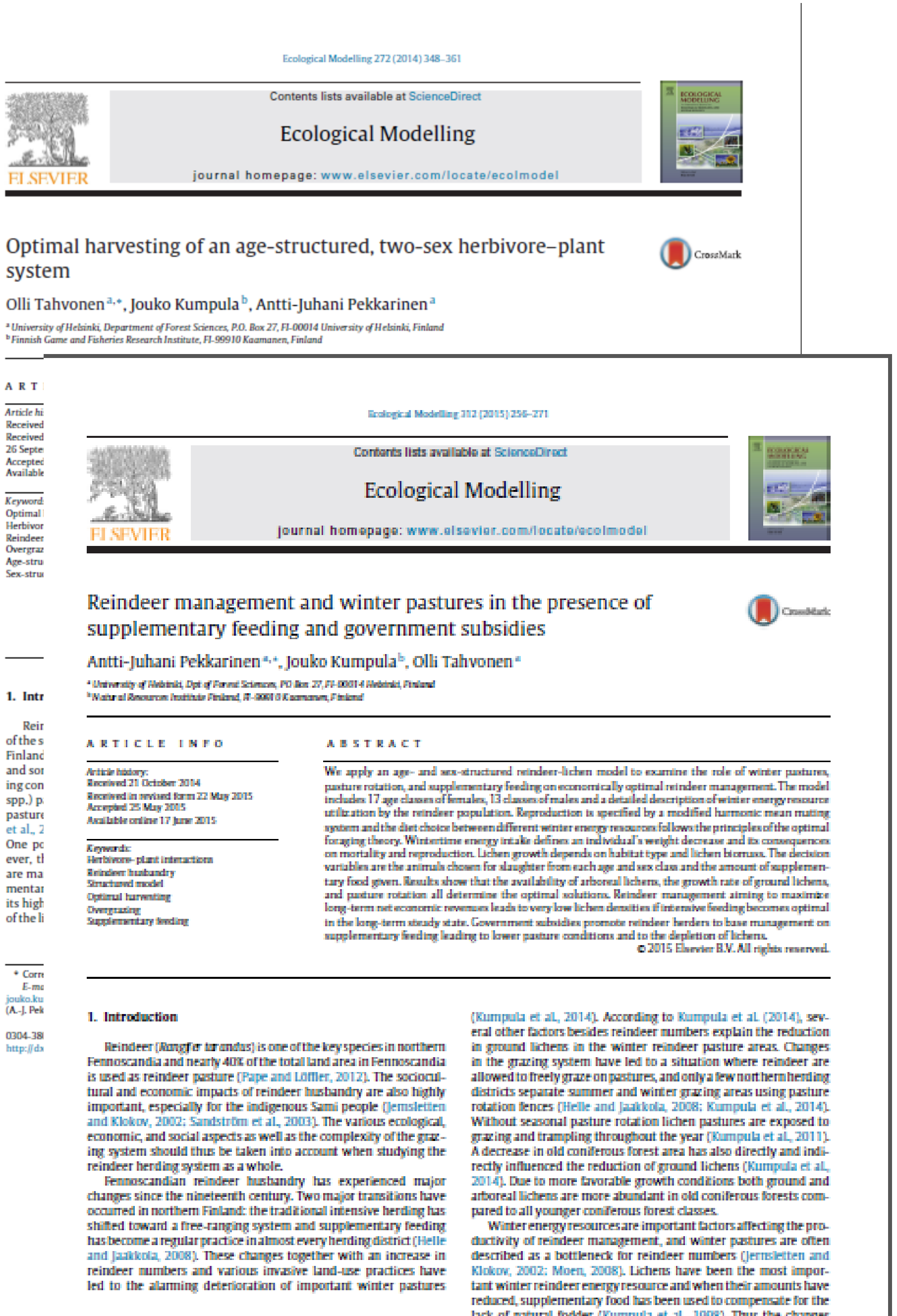
Spruce: 27.5-42.5 cm

Birch: 22.5-37.5 cm

Pine: 22.5-37.5 cm

Tahvonen and Rämö 2017

Example 4: reindeer management



Ecological Modelling 272 (2014) 348–361

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Optimal harvesting of an age-structured, two-sex herbivore–plant system

Olli Tahvonen[a,*], Jouko Kumpula[b], Antti-Juhani Pekkarinen[a]

[a] University of Helsinki, Department of Forest Sciences, P.O. Box 27, FI-00014 University of Helsinki, Finland
[b] Finnish Game and Fisheries Research Institute, FI-99910 Kaamanen, Finland

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Reindeer management and winter pastures in the presence of supplementary feeding and government subsidies

Antti-Juhani Pekkarinen[a,*], Jouko Kumpula[b], Olli Tahvonen[a]

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Overgrazing
Supplementary feeding

ABSTRACT

We apply an age- and sex-structured reindeer-lichen model to examine the role of winter pastures, pasture rotation, and supplementary feeding on economically optimal reindeer management. The model includes 17 age classes of females, 13 classes of males and a detailed description of winter energy resource utilization by the reindeer population. Reproduction is specified by a modified harmonic mean mating system and the diet choice between different winter energy resources follows the principles of the optimal foraging theory. Wintertime energy intake defines an individual's weight decrease and its consequences on mortality and reproduction. Lichen growth depends on habitat type and lichen biomass. The decision variables are the animals chosen for slaughter from each age and sex class and the amount of supplementary food given. Results show that the availability of arboreal lichens, the growth rate of ground lichens, and pasture rotation all determine the optimal solutions. Reindeer management aiming to maximize long-term net economic revenues leads to very low lichen densities if intensive feeding becomes optimal in the long-term steady state. Government subsidies promote reindeer herders to base management on supplementary feeding leading to lower pasture conditions and to the depletion of lichens.

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1. Introduction

The setup

- A model for reindeer population dynamics was specified as a joint task of ecologists and economists (no suitable model existed)
- Model is used to understand the economics and ecology of reindeer management
- Number of state variables ~30
- Optimization by gradient based methods (AMPL/knitro)

Results:

- Estimates on optimal reindeer population age and sex structure, harvesting strategy & reindeer and lichen density and the economic consequences of predators and government policy
- Calf harvesting optimal and applied in practice

Problems:

- For some model elements existing ecological knowledge is scarce
- 95% of reindeer studies consider various biological details and rather few offer understanding that could be used in these kind of studies

Criticism obtained: still under demand

Example 5: fisheries


ARTICLE IN PRESS

Journal of Environmental Economics and Management

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Economics of harvesting age-structured fish populations

ICES Journal of Marine Science Advance Access published May 9, 2011

Temperature change and Baltic sprat: from observations to ecological–economic modelling

Global Change Biology

It is the economy, stupid! Projecting the fate of fish populations using ecological–economic modeling

MARTIN F. QUAAS, THORSTEN B. H. REUSCH, JÖRN O. SCHMIDT, OLLI TAHVONEN

Author's personal copy

Environ Resource Econ (2013) 54:21–39
DOI 10.1007/s10640-012-9579-x

Optimal Harvesting of an Age-Structured Schooling Fishery

Olli Tahvonen · Martin Friedrich Quaas · Jörn Oliver Schmidt · Rudi Voss

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© Springer Science+Business Media B.V. 2012

Abstract Biologists have criticized traditional biomass models in fishery economics for being oversimplified. Biological stock assessment models are more sophisticated with regard to biological content, but rarely account for economic objectives. This study includes a full age-structured population model for studying schooling fisheries and extends the delayed difference approach used in earlier studies. We take the total harvest as the choice variable, resulting in a simple analytical structure. The model produces optimal steady states that may be higher or lower compared to the delayed-difference formulation. The model is applied to the Baltic sprat fishery. Both ecological and harvesting cost data support specifying Baltic sprat as a schooling fishery. Given nonlinear harvesting costs, the optimal solution is a path toward a steady state with smooth annual harvest and population age structure. Sensitivity analysis shows that the optimal solution is highly dependent on the population level of the sprat's main predator Baltic cod. A linear cost function and an interest rate below 9 % imply pulse fishing instead of smooth continuous harvesting. Given nonlinear harvesting cost, the optimal steady state yield is rather insensitive to changes in the interest rate. However, under a high cod scenario, interest rates of 10 % or higher implies that no optimal steady state exists.

Keywords Age-structured models · Optimal harvesting · Economic-ecological optimization · Fishery management · Multispecies interaction

JEL Classification Q22 · Q57 · Q28

O. Tahvonen
Department of Forest Sciences, University of Helsinki, Latokartanonkaari 7, P.L. 27, 00014 Helsinki, Finland
e-mail: olli.Tahvonen@helsinki.fi

M. F. Quaas · J. O. Schmidt · R. Voss
Department of Economics, University of Kiel, Wilhelm-Seelig-Platz 1, 24118 Kiel, Germany

The setup

- Developing the economics of fisheries based on age-structured ecological models (instead of classic biomass models)
- Research group includes ecologists and economists
- Ecological models are estimated by ecologists for the purposes of these projects
- Ecological model: age-structured population model with stochastic and deterministic recruitment

Results:

- Many "fundamental" economic results based on simple biomass models are found invalid
- MSY may yield major economic losses in fisheries

Problems:

- Difficult to obtain "simple" analytical results preferred by economists
- "Is this biology or economics"
  =>results easier to publish in ecological journals

Some common problems in economics-ecology model coupling

1. Ecological models are sometimes specified directly for some given management regime

- It is a limitation if growth and yield models are reliable only assuming timber harvesting follows the present practice, MSY,…
- At least earlier forest models were not suitable to describe thinning from above
- Natural regeneration is typically excluded
- Most models are only for single species
- Most models are only for even-aged stands
- Often commitment to some forest policy or management regime is implicit in forestry models
  =>difficult to proceed, is it possible to generalize the model?
  =>need for more data, experiments to produce data
  =>switch to process based models
- Note: economics may give ideas to which direction ecological models should be developed

2. Optimization may reveal problems in the ecological model

- In the optimization process the model is computed with a high number of different initial states and control variable trajectories (perhaps millions)
- This may reveal problems that cannot be found by computing the model with some low number of scenarios

  =>is it possible to fix the model in cooperation with ecologists?

3. Optimal solutions fall outside the “reliable domain” of the ecological model

- A common problem, examples: thinning from above in forestry, CCF
- Cannot be fixed by restricting the admissible solution space
- Many studies do not report whether or not this has been the case

=>is it possible to extend the ecological model in cooperation with ecologists?

4. Ecological model includes features that are “inconvenient” for optimization

- nonconvexities, functions not differentiable, functions not continuous,
- period length does not make economic sense,…

=>economists should be ready to apply optimization methods not typically used in economics

=>learning, cooperation with mathematicians

5. The economic optimization-ecological model system works but results are somehow “strange”

- Conflict with “practice” or with existing science
- Potentially fruitful situation or something is wrong in the models
- Cf. illegal rotation periods and thinning type results in forestry, pulse fishing in fishery

6. The source code of the ecological model is not openly available

- Not possible to publish reproducible research
- Has been the problem with one Finnish forestry model

7. The underlying empirically estimated ecological models have not been published in peer reviewed journals

- This has been the problem with a Swedish forest planning system: the estimation and specification of the underlying diameter growth, mortality, regeneration etc models have not been published in scientific journals

Summary

- Many questions on renewable resources can be studied as single discipline questions
- But some others are natural to study applying interdisciplinary setups
- This can be done by model coupling
- If the ecological model is a dynamic system that includes state and control variables the possibilities for model coupling exist
- Very seldom the ecological model is directly suitable for economic optimization
- To fix the problems it is necessary to cooperate across disciplines
- Interdisciplinary studies may have strong real world impact (cf. Geld, Kahneman, Clark)
- A warning: sometimes no one is very happy about the interdisciplinary study results (in the short run)