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## Human Behavior, decision making, and ABM+LUCC (mostly papers with ABMs, some other gems about the topic more generally)

Li An writes great reviews. Maja Schluter's work is awesome. Burkhard and Ma, Le, Murray-Rust and Villamor are other favorites of mine.

### References in my annotated bibliography

NOTE: The following are annotated in my personal notes at the end of this document. The notes aren't cleaned up; lots of abbreviated words and personal asides, but may be helpful nonetheless if someone is trying to get a feel for the range of models. Many papers utilize a core model (LUDAS, ARIES, etc). The notes help group them accordingly, and also a bit by their characteristics. They are ordered below according to the notes, rather than alphabetically.

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# MY ANNOTATED BIBLIOGRAPHY

### GENERAL COMMENTS:

The most common link between social ABM and anything biophysical is with LUCC. These papers are a dime a dozen. However, these aren't really getting at ecosystem services dynamically.

A number of esvc papers cite the need to account for "more from the human domain." There are several that take a bio-economic approach to including decisionmaking. But nobody's thinking all the way through to assets & adaptive capacities. A few come close: Kenny 2017; Turner et 2016; van Wijk et 2012; Malawska et 2014*. Still need to search explicitly for SLF and adaptive capacity papers w ABMs.*

Burkhardt et 2014: talks about esvc potentials, flows, benefits, demands.

* For regulating services, there's not much distinction between the potential and the flow
* But for provisioning they are NOT the same thing. This is THE GAP.
* (For cultural services, I'd need to think more about that one)
* Some esvces are rivalrous
* Talks plenty about supplies and demands (consumption),
* But very little about esvc PRODUCTION, though clearly articulates that other forms of capital are employed to turn provisioning potential into services, citing Costanza & Daly 1992, Costanza 2008)
* this paper doesn't follow the cascade through to valuation, preferences. The value of an ecosystem service potential is going to be low to anyone who can't access it!

Bastian et al 2014: talks about ecosystem properties (structures&fxns), potentials, and services EPPS

Brown et 2017 – incorporating behavior into clim change adaptation modelsRounsevell, Robinson et al. (2012). From actors to agents in socio-ecological systems models. Philosophical Transactions of the Royal Society B: Biological Sciences. **367:** 259-269.

* reviews all the complex social factors that mediate decision making
* stresses these are esp important in clim change adaptation
* basing models on past behav misses possibility of changed perceptions, motivations, institutional responses, etc
* AWESOME table of mostly ABM studies of adaptation in several sectors, mostly commercial ag
  + Subsistence ag is its own sector, v. few articles surprisingly
* In contrast to the introduction, their categoriz and lit review doesn't talk about the kinds of variables that behaviors are affected by.
* The livelihood adaptation gap remains unmentioned…

In all that I've read, adaptation is treated just as a decisionmaking point, not a **process**.

Zvolkeff & An: great review of landscape-human integrated methods. Lists many of the key articles and names.

Schulter et 2017:

* discuss how different theories of human decision making behavior are reflected in the way ABMs are designed…
* A framework for choosing the "right" decision model

Groenveld et 2017:

* review of LUCC AMB models, looking for theories of decision-making.
* Most are economic (worse yet, rational actor/expected utility), fewer are psycholSun, Lorscheid et al. (2016). Simple or complicated agent-based models? A complicated issue. Environmental Modelling & Software. **86:** 56-67.ogical

Balke & Gilbert 2014:

* Gets into details of decision theories, including Belief Desire Intent, as well as eBDI (emotional)
* "eBDI includes an internal representation of an agent's resources and capabilities"; an agent may not be aware of all its resources and capabilities. They are aware of Effective capabilities & resources.
* \*\*This sounds like SLF more than emotions to me!\*\*

Schulze et 2017 bring up all sorts of caveats about ABMs in SES

Filatova et 2013 focus on 4 key challenges in ABMs in SES, nice review

From Foxon et 2013: *Institutional economics* highlights the role of institutions

or ‘social rule systems’ in both enabling and constraining the choices of individual

economic actors (see, e.g., Vatn, 2005; for a summary of the literature, see

Hodgson, 2001)

Vatn, A. 2005. *Institutions and the Environment*, Cheltenham, Edward Elgar

Hodgson, G. 2001. Institutional economics, pp. 824–5 in Michie, J. (ed.), *Reader’s Guide to the*

*Social Sciences*, London, Routledge

Rounsevell et 2012 – seem to be explaining/justifying social ABMs to a nat sci audience

Kelly et 2013: review of ABM as well as SD, Bayesian, knowledge approaches to integrative models.

* Great table of key articles employing each approach & their characteristics

Voinov & Shugart 2013 – catchy article explaining how integral and integrated models can get way too far into the technical weeds, and end up being not useful at all.

Davies & Bennett 2007

" The livelihoods approach has arisen from failures in socio-economic research, particularly the overt focus on income and consumption, or costs and benefits, and the failure to explore the indirect impacts of change, distribution and entry-barriers (Boyd et al., 1999). The livelihoods approach puts people, particularly the poor, at the centre of development planning, which demands a recognition of their goals and aspirations. This in turn requires a sound knowledge of poverty and of what people lack when they are impoverished. This is particularly pertinent in the lowland areas of Ethiopia where pastoralists have survived for centuries in their rangeland environments through the development of complex livelihood strategies. A failure to understand how these strategies operate can allow policies to be adopted that will undermine existing survival mechanisms."

\*Kenny 2017: reviews models useful for natural and social capital.

"No model exists that integrates full consideration of both natural and social capital into a full-cost calculation of risk, resilience, and well-being for farm systems, despite a clear need for such a model. The use of models to understand and explore human-ecosystem interactions, particularly with farms, is not a new development, but a model that proposes to incorporate concepts of the various types of capital to assess such a system holds great potential."

* Thank you, Kenny. We agree!

Turner et 2016: review of esvc assessments, focusing on 4 capitals

* argue that nat cap provides svces when combined with human, built, & soc cap
* note the current lack of attn. to human demand for esvces (models focus on supply)
* But in their approach, they Look @ very large scale indicators of human cap (pop, educ stats, devel index), built (GDP, impervious surfaces, ecol footprint), come up short on social (phone lines?!)
* Nowhere near adaption or SLF
* Reviews valuation methods
* BIG table of models for land mgmt. effects
* Big table of ecosystem service tools from bagstad et 2013

Eigenbrod et 2010 – caution against landscape proxies for esvces. Weak correls to primary data

Van Wijk et 2012 – review looking for farm models that deal with adaptation & climate change

" There is a need for more explicit farm level analyses with a focus on adaptation, vulnerability and risk. In general terms, this systematic review concludes that there are enough techniques for integrated assessments of farm systems in relation to climate change, adaptation and mitigation, but they have not yet been combined in a way that is meaningful to farm level decision makers."

* The review was very economic and food security focused.
* Huge lists of math programming and some ABM models (p23)
* "IRRIGATE" (Merot & Bergez 2010) is a "biodecision model", simulating decision-making
* Still nothing really on assets & constraints for adaptation!

Braat & de Groot 2012 – Ecosystem services agenda review

* Excellent history of the ecol & econ roots of the esvc concept, going back to GPMarsh!
* The rest focuses on assessment, valuation, mgmt. of values

### ABM MODELING PAPERS:

*Ones with no description: I only read enough to determine what their model did*

Parker et 2003 – classic reference

* Revew of different LULCC + ABM efforts; table of papers up till then.
* Makes great points about ABMs in handling complexity, adaptation, emergence, alt pathways
* Way ahead of its time… cited 1597 times!

Other classics:

Evans & Kelley 2004 LUCC+ABM

* Utility maximize approach, agents w different land use portfolio preferences
* Results change somewhat with spat resolut of input data
* Heavily cited, not my fave

Bosquet & Le Page 2004 – my least favorite.

Matthews et 2007 – describes AB land use models according to their uses

Describes a lot of different ABLUMs

Concludes they're better for research to understand systems than policy tools

Dumrongrojwatthana et 2011 – partic ABM (companion modeling)

* This is where ABM has really valuable role in decisionmaking
* Impressive study: 2 day workshop. Co constructed veg transitions, stakeholders worked through scenarios
* Herders and foresters began to cooperate. Very cool.

Sun et 2016 – How complicated should an ABM be?

* Practical guidance for building ABMS that are not too complicated.
* Will be useful for me to read before workshop!

Parker et 2008 – Review of LUCC ABM challenges & interesting issues,

* Eclectic, intelligent article with some interesting nuggets. Conceptual.
* Deviations from optimistic economic approaches that people will not deplete resources
* Highlights interesting research questions that ABMs can address: threshold phenomena, framing effects, cross scale interx, identifying a minimum set of state variables, one way & two way linkages between natural and social

*Chen et 2012*

*Acevedo et 2008*

*Entwisle et 2008 LUCC + ABM*

*Deadman et 2004 LUCC + ABM*

*Badmos et 2015 soil loss + ABM*

*\*\*Mialhe et 2012 LUC + ABM Netlogo. Very promising*

*Different rationalities*

*Uncertainties*

*Random "disasters"*

\*Matthews 2006 PALM biophysical + ABM \*Mentions SLA\*

- describes shortcomings of other models wrt some of the things we want to achieve

- good source for making our case

- decisiomaking uses "ethnographic decision tree"

-ecological dynamics are intensely modeled, DSSAT, CropGRO and some livestock models

*- Should see who's cited this…*

*Martin et 2016 rangeland dynamics + ABM … looks promising*

*\*\*Huber et 2013 veg dynamics + PES + ABM … looks promising*

*Morgan et 2015 env optimiz model + ABM*

*Tesfatsion et 2017 watershed + ABM WACCshed model*

Bert et 2011 – structural & LUCC + AMB

* gives really helpful comparison of workflows and rules of different models, but no ecol fdbks

\*Schreinemachers & Berger 2011 MP-MAS model:

- ABM with ecosystem feedbacks

- has set of biophysical modules you can use with it

- Motherlode of articles citing it…

Carauta et 2017 "bioeconomic microsimulation"

* Process based crop simulator MONICA with MP-MAS

Wossen & Berger 2015 – MPMAS to look @ climate adaptation (bioeconomic)

* Do mention agentscan have "heterogeneous resource endowments & adapting capacity"….
* But I didn't see how they represented that in this simulation.
* Used MPMAS to look at effects of credit and off-farm income on per cap income under scenarios with climate change and food price variability
* Pretty technical. Used CROPWAT as biophys submodel

Wossen et 2017 – MPMAS and climate/price var adaptation (Ghana & Ethiopia)

* Again mention "adaptive capacity of households & availability of options"
* Agents maximize income "subject to production and consumption preferences as well as resource endowments (such as labor, capital, land, and water)."
* But I don't see it. I just see them assigning a distrib of wealth to HHs
* May need to go back to MPMAS 2011 to look for this…

Quang et 2014 another MPMAS, focus on effects of conservation methods on soil loss

Sahrbacher et 2014 AgriPoliS model: trying to put ES into AgriPoliS, a structural change model

Evans & Kelley 2004 LUCC+ABM

* Utility maximize approach, agents w different land use portfolio preferences
* Results change somewhat with spat resolt of input data

Evans et 2011 LUCC+ABM applied to adopting rubber plantations in Laos

* Utility maximiz with minimal asset based decisions (labor, income set thresholds to innovate)

\*Rasch et 2016 SAfr livestock SES ABM

- The model was designed for scientists who study the impact of social norms on SES dynamics in common-pool resource settings

\*Rasch et 2017 SAfr livestock SES ABM HH and system resilience

\*Le et 2008, 2010 – LUDAS (landscape ABM of veg dynamics + HH ABM)

* I like that landscape agents have human-influenced and internal ecological variables
* Layout in 2008 is ultra clear; I can see how this could be modified to include more complex transition functions, track ES variables, etc.
* Already exists as a coupled landscape-household multi-agent model in NetLogo!

Villamor et 2016 – LUDAS w gendered decisions

* Fascinating parallel betw ABM and RPG to look at gender in LUCC decisions,
* Included PES scenario
* LUDAS is cool but ecological modules are complicated & need a lot of data
* LUDAS needs a whole major paramateriz for ea new system

\*Villamor et 2014 – LUDAS with subsidies and PES, rubber agroforestry

- the decisionmaking had many cool aspects and allowed learning as well as watching neighbors

- discussed 1\* and 2\* s-e feedbacks, first bioeconomic, 2nd thru learning & changing strategy

- enjoyed this paper a lot. Social validation thru role playing

\*Miyasaka et 2017 – LUDAS for inner mongolia

\*Habib et 2016 – ABM of multiple esvc dynamics (timber growth, C storage, water purific), then some ABM generated pdtion functions (pollination, biodiversity)

- decision making is just the choice of land uses in a contrives scenario

- uses NetLogo!

Dou 2016- dissertation: cash transfers & rural livelihoods in brazil (under Deadman)

* Decision making strategy had biggest impact on hh and community livelihoods

\* Iwamura et 2014 – multi agent (land, villages, households, animals), all as ABM in Netlogo

- land use change and livelihood strategies (hunting & ag)

- great description of their model

- had lots of deterministic fxns for agent transitions

- decisions based on energetics and food sufficiency

- from a CNH 0508094

Murray-Rust et 2011 LUCC ABM Esvces

* Esvces as calculated from dynamic veg model outputs, not co-created
* Paper does have a helpful diagram of how to integrate all the various social factors into decisionmaking vis a vis the "evaluation function" (p90)
* Use empirical data to define typologies of agent behavior
* Conjoint analysis sets up matrix of attributes & options for each, to assign behavs to ea possible combination
* They didn't build the abm. This became CRAFTY & Aporia (Murray-Rust et 2014 & 2014)

Murray-Rust et 2014 CRAFTY: LUCC ABM Esvc

* Operates @ large spatial scale
* Multifxn per pixel
* ***Each pixel has associated nat, human, fin, material capitals,*** which can change thru time
* Stylized, but heterogeneous decisionmaking strategies (agent types)
* Good for looking at tradeoffs in esvces

Brown et 2016 CRAFTY application

* Models agents with different visions/prefs for the future and different esvces
* Hard to get used to its large scale
* Ended up with daisy diagrams of mult services under different visions

Rammer & Seidl 2015 – coupled IBM (indiv trees) –ABM (2 time scales of forest mgmt. decisions)

* Nice motivation to couple dynamic ecological and decision making models
* Tidy but kind of narrow model: really about managing trees in forests.

\*Malawska & Topping 2016. Farm decision making ABM

- compared profit maximizing to models w bounded rationality & practical constraints

- cite holtz & nebel 2014 finding that rational vs. bounded affects outcomes.

- They found **practical constraints affected outcomes a lot more than bounded rationality**!

Olabisi et 2015 ABM farmers adopting organic ag

* Pretty simple homegrown model, used lots of prob fxns for transitions
* Behavs parameterized with qualitative field data
* Included social networks (innov diffusion)
* Good example to think about, perhaps for camels

Heckbert et 2009

* Moose pop dyn using standard logistic eqns
* Decision rules for road closures ea year
* ABM of hunter prefs
* Multi-agent based NetLOGO!

Vinatier et 2016 explain how to model immobile and mobile ecol agents in a landscape.

* People aren't a part of this ABM framework. After reading "how complicated should an ABM be?" (Sun et 2016), keeping the landscape agents to as few as possible seems advisable.

***Are there any sustainable livelihoods framework ABMs? More adaptive capacity focused ABMs?***

### ABM NAMES:

Polhill, Berger, Wossen, Filatova, Tesfatsion, Heckbert

### COUPLED MODELS:

(partly reviewed in Kenny 2017, another….)

MP-MAS

AgriPoliS

MP-MAS includes endogenous biophysical dynamics and is

tailored to the (ex post) assessment of agricultural innovations with most

applications to developing countries, whereas AgriPoliS is a more

economic simulation model tailored to (ex ante) assessing structural change

with all applications to European countries (Schirenemachers & Berger 2011)

WACCshed

ARIES (Bagstad et 2013)

LUDAS (le et 2008, 2010) – in NetLogo (also Miyasaka)

CRAFTY (Murray-Rust et 2014)

Aporia (Murray-Rust et 2014 Open…) – Meant for other users

* Great to enable building ag LUCC ABMs, but does not have households
* This is about commercial land use & esvces

PUMANI (Holtz & Pahl-Wolst 2011)

PALM (Matthews & Pilbeam 2005)

"IRRIGATE" (Merot & Bergez 2010) is a "biodecision model", simulating decision-making

### ESVC MODELS:

Generalized: reviewed in Bagstad et 2013; there are more in the article

InVEST

MIMES (from GUMBO)

ARIES

EcoServ

LUCI

-these are all biophysical or land use based,but don't use process-based modeling

-ecological data isn't really needed; service production functions are.

SolVES (social values)

Pimp Your Landscape tool (!): CA visualization to use with particip LUCC -> esvc change (Koschke et 2012). Generates daisy diagrams from multi criteria assessment

GISCAME – agent based spatial ecosystem service model (

* Maps ecosystem potentials and relates them to services (doesn't calculate service yields)
* Much less data dependent & heavily parameterized than invest and aries.

Koniak et 2011 – translates their veg change CA into esvces provided by each veg state

Van Oudenhoven et 2012 –

- follows Haines-Young and Potchkin (and degroot) by inserting more steps between nat cap and benefits

- ecosystem properties -> function indicators -> service indicators

- land mgmt. modulates the way one leads to the next (doesn't go as far as assets for land mgmt.)

Brady et 2012: uses agripolis, then calcs evces to evaluate different policy impacts on tradeoffs

* Ag productivity
* Biodiversity via species-area curves

Jorda-Capdevila et 2016:

Hydrology model of river system

Translated various outputs into water-related ES

Used participatory process to derive "suitability curves of es production" (Korsgaard et 2008)

Thereby translated hydrological model outputs into es provision levels

BAGSTAD et 2013: SPAN and ARIES

* SPAN: agent based model of (literal) flow of ecosystem services to beneficiaries
* Also follows Haines-Y & P idea of steps between nat cap and benefits: spatial steps
* SPAN is part of ARIES platform
* InVEST, in contrast, does not report flow results in a complete manner, no uncertainty estim

Tarrason: esvc assessment via local knowledge (partly…)

* Experts proposed relations between land degradation & varios esvces
* Participatory construction of veg STM, elicited local priorities for esvces

\*\*Bastian et 2012: EPPS Ecosystem Properties Potentials and Services

* This is in line with our central framing
* Landscape potential has been a longstanding concept in European landscape planning
* Also talks about multiple uses of the term capacity
* In Germany esvces are often called 'societal functions'
* They never deal with social potential on the "demand" side.

Haines-Young et 2012 (Indicators of esvc potential…):

* another one that focuses on nat cap🡪esvc, but doesn't mention other caps needed to turn stock into flow

Hainz-Renetzeder et 2015: mapping esvc potential

* translate veg maps into the potential reg, provis, cult services they can provide.
  + Used expert evaluation workshops to make those links
  + Matrix of veg type and 0-5 value for many different esvces

### DECISION/ABM MODELS:

LUCITA (deadman et al 2004)

### OTHER APPROACHES

Rova & Pranovi 2017: they reframe Esvces in terms of Ostrom SES, focusing on supply and demand sides, and the temporal lags between them

Huber et 2014. Integrated analysis of socioecon and climate change on suite of esvces

* Ecol expts, landscape dynamic models, socioecon land use models, policy analysis, stakeholder interactions.
* Nice table showing workflow of all these analytical components

Hammond and Dube 2012 – a PNAS paper that only has a conceptual framework.

Kennedy et 2016 – classic PFF optimiz w mult esvces for Brazil.

* Now it's kind of glaring when something like this just assumes a land use will give you a ROI

Walsh et 2008 – LUCC CA

* The cells have human attributes associated with them (land users I guess)
* Transition probabilities depend on updating states of those attributes
* Managed to condense a multiABM into a CA because of spatial coupling of human land use variables

Role Playing Games (RPG)

Participatory Planning with GIS (PPGIS)

Companion Modeling

# FULL ALPHABETICAL BIBLIOGRAPHY WITH ABSTRACTS (IF I HAD THEM IN ENDNOTE)

Bagstad, K. J., G. W. Johnson, B. Voigt and F. Villa (2013). "Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services." Ecosystem Services **4**: 117-125.

Recent ecosystem services research has highlighted the importance of spatial connectivity between ecosystems and their beneficiaries. Despite this need, a systematic approach to ecosystem service flow quantification has not yet emerged. In this article, we present such an approach, which we formalize as a class of agent-based models termed “Service Path Attribution Networks” (SPANs). These models, developed as part of the Artificial Intelligence for Ecosystem Services (ARIES) project, expand on ecosystem services classification terminology introduced by other authors. Conceptual elements needed to support flow modeling include a service's rivalness, its flow routing type (e.g., through hydrologic or transportation networks, lines of sight, or other approaches), and whether the benefit is supplied by an ecosystem's provision of a beneficial flow to people or by absorption of a detrimental flow before it reaches them. We describe our implementation of the SPAN framework for five ecosystem services and discuss how to generalize the approach to additional services. SPAN model outputs include maps of ecosystem service provision, use, depletion, and flows under theoretical, possible, actual, inaccessible, and blocked conditions. We highlight how these different ecosystem service flow maps could be used to support various types of decision making for conservation and resource management planning.

Bagstad, K. J., D. J. Semmens, S. Waage and R. Winthrop (2013). "A comparative assessment of decision-support tools for ecosystem services quantification and valuation." Ecosystem Services **5**: 27-39.

To enter widespread use, ecosystem service assessments need to be quantifiable, replicable, credible, flexible, and affordable. With recent growth in the field of ecosystem services, a variety of decision-support tools has emerged to support more systematic ecosystem services assessment. Despite the growing complexity of the tool landscape, thorough reviews of tools for identifying, assessing, modeling and in some cases monetarily valuing ecosystem services have generally been lacking. In this study, we describe 17 ecosystem services tools and rate their performance against eight evaluative criteria that gauge their readiness for widespread application in public- and private-sector decision making. We describe each of the tools′ intended uses, services modeled, analytical approaches, data requirements, and outputs, as well time requirements to run seven tools in a first comparative concurrent application of multiple tools to a common location – the San Pedro River watershed in southeast Arizona, USA, and northern Sonora, Mexico. Based on this work, we offer conclusions about these tools′ current ‘readiness’ for widespread application within both public- and private-sector decision making processes. Finally, we describe potential pathways forward to reduce the resource requirements for running ecosystem services models, which are essential to facilitate their more widespread use in environmental decision making.

Bagstad, K. J., D. J. Semmens and R. Winthrop (2013). "Comparing approaches to spatially explicit ecosystem service modeling: A case study from the San Pedro River, Arizona." Ecosystem Services **5**: 40-50.

Although the number of ecosystem service modeling tools has grown in recent years, quantitative comparative studies of these tools have been lacking. In this study, we applied two leading open-source, spatially explicit ecosystem services modeling tools – Artificial Intelligence for Ecosystem Services (ARIES) and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) – to the San Pedro River watershed in southeast Arizona, USA, and northern Sonora, Mexico. We modeled locally important services that both modeling systems could address – carbon, water, and scenic viewsheds. We then applied managerially relevant scenarios for urban growth and mesquite management to quantify ecosystem service changes. InVEST and ARIES use different modeling approaches and ecosystem services metrics; for carbon, metrics were more similar and results were more easily comparable than for viewsheds or water. However, findings demonstrate similar gains and losses of ecosystem services and conclusions when comparing effects across our scenarios. Results were more closely aligned for landscape-scale urban-growth scenarios and more divergent for a site-scale mesquite-management scenario. Follow-up studies, including testing in different geographic contexts, can improve our understanding of the strengths and weaknesses of these and other ecosystem services modeling tools as they move closer to readiness for supporting day-to-day resource management.

Balke, T. and N. Gilbert (2014). "How Do Agents Make Decisions? A Survey." Journal of Artificial Societies and Social Simulation **17**(4): 13.

When designing an agent-based simulation, an important question to answer is how to model the decision making processes of the agents in the system. A large number of agent decision making models can be found in the literature, each inspired by different aims and research questions. In this paper we provide a review of 14 agent decision making architectures that have attracted interest. They range from production-rule systems to psychologically- and neurologically-inspired approaches. For each of the architectures we give an overview of its design, highlight research questions that have been answered with its help and outline the reasons for the choice of the decision making model provided by the originators. Our goal is to provide guidelines about what kind of agent decision making model, with which level of simplicity or complexity, to use for which kind of research question.

Barnaud, C., E. Corbera, R. Muradian, N. Salliou, C. Sirami, A. Vialatte, J.-P. Choisis, N. Dendoncker, R. Mathevet, C. Moreau, V. Reyes-García, M. Boada, M. Deconchat, C. Cibien, S. Garnier, R. Maneja and M. Antona (2018). "Ecosystem services, social interdependencies, and collective action: a conceptual framework." Ecology and Society **23**(1).

The governance of ecosystem services (ES) has been predominantly thought of in terms of market or state-based instruments. Comparatively, collective action mechanisms have rarely been considered. This paper addresses this gap by proposing a conceptual framework that brings together ES, social interdependencies, and collective action thinking. We use an ES conceptual lens to highlight social interdependencies among people so as to reflect on existing or potential collective actions among them. This framework can also contribute to increasing people&#8217;s awareness of their mutual interdependencies and thereby fostering, framing, or enriching collective action, in ways that take into account the diversity and complexity of ecological processes underlying human activities. Our approach can contribute in particular to agroecological transitions that require landscape level innovations and coordination mechanisms among land users and managers. The framework distinguishes three types of social interdependencies: (i) between ES beneficiaries and ES providers, (ii) among beneficiaries, and (iii) among providers. These social interdependencies are in turn analyzed according to four main dimensions that are critical for collective action: (i) cognitive framing of interdependencies, (ii) levels of organization, (iii) formal and informal institutions, and (iv) power relations. Finally, we propose a strategy to turn this framework into action in contexts of participatory action research, a strategy grounded on a number of methodological principles and tools that convey complexity and increase people&#8217;s awareness of interdependencies in agrarian social-ecological systems.

Bastian, O., D. Haase and K. Grunewald (2012). "Ecosystem properties, potentials and services – The EPPS conceptual framework and an urban application example." Ecological Indicators **21**: 7-16.

The concept of ecosystem services is an approach widely discussed to clarify and to assess the dependence of human society on ecosystems and landscapes. In order to better differentiate between the potential performance of ecosystems and landscapes and the quality needed or demanded by society, in this paper we suggest returning to the landscape potential concept developed by landscape ecologists in the 1970s. Emerging from both concepts is the hereinafter discussed EPPS framework – ecosystem (or landscape) properties, potentials and services – which is a way to better link both potentials and services to current planning and management practice and governance schemes. The empirical part of the paper shows applications of the EPPS framework in an urban region.

Bastian, O., R.-U. Syrbe, M. Rosenberg, D. Rahe and K. Grunewald (2013). "The five pillar EPPS framework for quantifying, mapping and managing ecosystem services." Ecosystem Services **4**: 15-24.

This paper introduces an ecosystem services assessment framework with five pillars: ecosystem properties, potentials, services, benefits/values, and beneficiaries. In a case study in the district of Görlitz (Eastern Saxony, Germany), we present an exemplary application for two ecosystem services: crop food production and soil erosion regulation. The farmland of the district can produce a total of about 518,000 t of crop food (rye) per year, depending on yield potential. Corrected for the mean price of the crop rye, this translates to a value of about 100 million € annually. At the same time, 606,000 t of soil loss must be calculated per year, which corresponds to 36 million € in damages. If 7% of the farmland were to be transformed into grassland or forest, the provisioning service would sink by 37,000 t of rye, for an income loss of approx. €7.4 million per year. On the other hand, soil erosion regulation would be enhanced and soil loss would be reduced by c. 20%, corresponding to on-site benefit of €7.1 million. Within a more intensively used partial study area (with dominating loess soils), the benefits of the erosion regulation service (€656,000) exceed the yield losses (€245,000) more than twice.

Batie, S. S. (2008). "Wicked Problems and Applied Economics." American Journal of Agricultural Economics **90**(5): 1176-1191.

The term “wicked problems” is found in many disciplines, including public administration, policy science, health education, ecology, forestry, and business administration, but the term is relatively unknown in applied economics. Applied economics needs to become better acquainted with wicked problems; they are pervasive, and they present challenges if applied economics is to retain its relevance in today's world. This paper explores these challenges but is necessarily exploratory, as widespread recognition of the complexity of wicked problems is leading to new kinds of research, but these research approaches are still evolving. My basic thesis is that normal science assumptions and approaches are inadequate for addressing the complexities of wicked problems in a policy context, but that science, including social science, remains crucial for the development of alternative policies. This exploration, therefore, is about both the characteristics of postnormal science necessary to inform alternative policies designed to address wicked problems as well as their implications for policy contributions from applied economics. Because many wicked problems involve sustainability issues, I will focus mainly on sustainability problems.

Bebbington, A. (1999). "Capitals and Capabilities: A Framework for Analyzing Peasant Viability, Rural Livelihoods and Poverty." World Development **27**(12): 2021-2044.

On the basis of themes emerging in current debates on rural development in Latin America, this paper develops an analytical framework for analyzing rural livelihoods in terms of their sustainability and their implications for rural poverty. The framework argues that our analyses of rural livelihoods need to understand them in terms of: (a) people’s access to five types of capital asset; (b) the ways in which they combine and transform those assets in the building of livelihoods that as far as possible meet their material and their experiential needs; (c) the ways in which people are able to expand their asset bases through engaging with other actors through relationships governed by the logics of the state, market and civil society; and (d) the ways in which they are able to deploy and enhance their capabilities both to make living more meaningful and to change the dominant rules and relationships governing the ways in which resources are controlled, distributed and transformed in society. Particular attention is paid to the importance of social capital as an asset through which people are able to widen their access to resources and other actors.

Bennett, E. M. (2017). "Research Frontiers in Ecosystem Service Science." Ecosystems **20**(1): 31-37.

How are ecosystem services conceptualized, analyzed, and forecast into the future? How can ecosystem service science be advanced to improve environmental decision-making at all scales? In this paper, I focus on three critical challenges in ecosystem service science that must be addressed to better understand, forecast, and manage ecosystem services. These include (1) understanding the role of nonlinearities, feedbacks, and legacies in the sustainable and resilient provision of ecosystem services; (2) understanding the role and interplay of ecological and social components in the provision of ecosystem services; and (3) employing stakeholder knowledge in co-designing research that better addresses decision-makers’ most pressing questions. Addressing these three challenges will advance ecosystem science and improve the use of ecosystem services in understanding and managing ecosystems.

Bennett, E. M., W. Cramer, A. Begossi, G. Cundill, S. Díaz, B. N. Egoh, I. R. Geijzendorffer, C. B. Krug, S. Lavorel, E. Lazos, L. Lebel, B. Martín-López, P. Meyfroidt, H. A. Mooney, J. L. Nel, U. Pascual, K. Payet, N. P. Harguindeguy, G. D. Peterson, A.-H. Prieur-Richard, B. Reyers, P. Roebeling, R. Seppelt, M. Solan, P. Tschakert, T. Tscharntke, B. L. Turner, P. H. Verburg, E. F. Viglizzo, P. C. L. White and G. Woodward (2015). "Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability." Current Opinion in Environmental Sustainability **14**(Supplement C): 76-85.

Ecosystem services have become a mainstream concept for the expression of values assigned by people to various functions of ecosystems. Even though the introduction of the concept has initiated a vast amount of research, progress in using this knowledge for sustainable resource use remains insufficient. We see a need to broaden the scope of research to answer three key questions that we believe will improve incorporation of ecosystem service research into decision-making for the sustainable use of natural resources to improve human well-being: (i) how are ecosystem services co-produced by social–ecological systems, (ii) who benefits from the provision of ecosystem services, and (iii) what are the best practices for the governance of ecosystem services? Here, we present these key questions, the rationale behind them, and their related scientific challenges in a globally coordinated research programme aimed towards improving sustainable ecosystem management. These questions will frame the activities of ecoSERVICES, formerly a DIVERSITAS project and now a project of Future Earth, in its role as a platform to foster global coordination of multidisciplinary sustainability science through the lens of ecosystem services.

Berbés-Blázquez, M., M. J. Bunch, P. R. Mulvihill, G. D. Peterson and B. van Wendel de Joode (2017). "Understanding how access shapes the transformation of ecosystem services to human well-being with an example from Costa Rica." Ecosystem Services **28**(Part C): 320-327.

Increasingly, ecosystem services have been applied to guide poverty alleviation and sustainable development in resource-dependent communities. Yet, questions of access, which are paramount in determining benefits from the production of ecosystem services, remain theoretically underdeveloped. That is, ecosystem assessments typically have paid little attention to identifying real or hypothetical beneficiaries and the mechanisms by which benefits may be realized. This limits their ability to guide policy and interventions at the local scale. Through a qualitative mixed methods approach, this article analyzes how access to different aspects of the production of provisioning services is negotiated in Bribri communities (Costa Rica) of small-scale plantain farmers with alternative modes of agricultural production. The analysis considers access to land, labour, knowledge, tools, markets, and credit. Our analysis reveals how institutions of access are organized differently in traditional vs. conventional systems of agriculture and how these shape power dynamics and pathways to well-being. We conclude that understanding institutions regulating access to ecosystem services provides more useful insights for poverty alleviation than approaches that assume homogeneous access to benefits.

Bert, F. E., G. P. Podestá, S. L. Rovere, Á. N. Menéndez, M. North, E. Tatara, C. E. Laciana, E. Weber and F. R. Toranzo (2011). "An agent based model to simulate structural and land use changes in agricultural systems of the argentine pampas." Ecological Modelling **222**(19): 3486-3499.

The Argentine Pampas, one of the main agricultural areas in the world, recently has undergone significant changes in land use and structural characteristics of agricultural production systems. Concerns about the environmental and societal impacts of the changes motivated development of an agent-based model (ABM) to gain insight on processes underlying recent observed patterns. The model is described following a standard protocol (ODD). Results are discussed for an initial set of simplified simulations performed to understand the processes that generated and magnified the changes in the Pampas. Changes in the structure of agricultural production and land tenure seem to be driven by differences among farmers’ ability to generate sufficient agricultural income to remain in business. In turn, as no off-farm or credit is modeled, economic sustainability is tied to initial resource endowment (area cropped). Farmers operating small areas are economically unviable and must lease out their farms to farmers operating larger areas. This leads to two patterns: (a) a concentration of production (fewer farmers operating larger areas) and, (b) an increase in the area operated by tenants. The simulations showed an increase of soybean area, linked to the higher profitability of this crop. Despite the stylized nature of initial simulations, all emerging patterns are highly consistent with changes observed in the Pampas.

Bieling, C., T. Plieninger, H. Pirker and C. R. Vogl (2014). "Linkages between landscapes and human well-being: An empirical exploration with short interviews." Ecological Economics **105**(Supplement C): 19-30.

Human well-being is tightly linked to the natural environment. Although this notion is well-established, it remains difficult to assess how the biophysical features of a specific area contribute towards the well-being of the people attached to it. We explore this topic using the case of four areas in Germany and Austria by performing open, single-question interviews with 262 respondents. Data reveal an outstanding relevance of nonmaterial values. Linkages between landscapes and human well-being are tied to specific features of the material environment but, likewise, practices and experiences play an important role in the creation and acknowledgment of such values. Our results accord with the conceptual outline of the cultural values model but fit to a lesser degree into the ecosystem services framework. Due to the high relevance of experiential factors, providing manifold opportunities for people to engage with their natural surroundings should be considered a strategy for fostering human well-being.

Biggs, R., M. Schlüter, D. Biggs, E. L. Bohensky, S. BurnSilver, G. Cundill, V. Dakos, T. M. Daw, L. S. Evans, K. Kotschy, A. M. Leitch, C. Meek, A. Quinlan, C. Raudsepp-Hearne, M. D. Robards, M. L. Schoon, L. Schultz and P. C. West (2012). "Toward Principles for Enhancing the Resilience of Ecosystem Services." Annual Review of Environment and Resources **37**(1): 421-448.

Enhancing the resilience of ecosystem services (ES) that underpin human well-being is critical for meeting current and future societal needs, and requires specific governance and management policies. Using the literature, we identify seven generic policy-relevant principles for enhancing the resilience of desired ES in the face of disturbance and ongoing change in social-ecological systems (SES). These principles are (P1) maintain diversity and redundancy, (P2) manage connectivity, (P3) manage slow variables and feedbacks, (P4) foster an understanding of SES as complex adaptive systems (CAS), (P5) encourage learning and experimentation, (P6) broaden participation, and (P7) promote polycentric governance systems. We briefly define each principle, review how and when it enhances the resilience of ES, and conclude with major research gaps. In practice, the principles often co-occur and are highly interdependent. Key future needs are to better understand these interdependencies and to operationalize and apply the principles in different policy and management contexts.

Braat, L. C. and R. de Groot (2012). "The ecosystem services agenda:bridging the worlds of natural science and economics, conservation and development, and public and private policy." Ecosystem Services **1**(1): 4-15.

The Ecosystem Services Journal starts in 2012 with a formidable basis in the reports and books from the Millennium Ecosystem Assessment and TEEB projects. Following a half-century history of growing awareness and associated scientific based policy development a bridging concept with natural and social science notions was developed and coined “ecosystem services”. The agenda for the journal Ecosystem Services, presented in this introductory paper to the Journal Ecosystem Services is aimed at scientists and policy analysts who consider contributing to better knowledge and better use of that knowledge about ecosystem services. This should include knowledge of the ecological systems that provide the services, the economic systems that benefit from them, and the institutions that need to develop effective codes for a sustainable use. The agenda is derived from the experience of the authors in science and policy analysis and extended with some of the recommendations from the TEEB book for national and international policy making emphasising the science—policy—practice linkage, which is the philosophy of the Journal.

Brady, M., C. Sahrbacher, K. Kellermann and K. Happe (2012). "An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services." Landscape Ecology **27**(9): 1363-1381.

We present extensions to the agent-based agricultural policy simulator (AgriPoliS) model that make it possible to simulate the consequences of agricultural policy reform on farmers’ land use decisions and concomitant impacts on landscape mosaic, biodiversity and ecosystem services in a real agricultural region. An observed population of farms is modelled as a multi-agent system where individual farm-agent behaviour and their interactions—principally competition for land—are defined through an optimization framework with land use and landscape impacts resulting as emergent properties of the system. The model is calibrated to real data on the farms and the landscape to be studied. We illustrate the utility of the model by evaluating the potential impacts of three alternative frameworks for the European Union Common Agricultural Policy (CAP) on landscape values in two marginal agricultural regions. Mosaic value was found to be sensitive to the choice of policy scheme in one of the landscapes, whereas significant trade-offs were shown to occur in terms of species richness by habitat and species composition at the landscape scale in both regions. The relationship between food production and other ecosystem services was found to be multifaceted. Thus illustrating the difficulty of achieving landscape goals in a particular region with simple or general land management rules (such as the current rules attached to CAPs direct payments). Given the scarcity of funding for conservation, the level and conditions for allocating direct payments are, potentially, of great importance for preserving landscape values in marginal agricultural regions (subject to levels of other support).

Brown, C., P. Alexander, S. Holzhauer and M. D. A. Rounsevell (2017). "Behavioral models of climate change adaptation and mitigation in land-based sectors." Wiley Interdisciplinary Reviews: Climate Change **8**(2): e448-n/a.

Models of the land system are essential to our understanding of the magnitude and impacts of climate change. These models are required to represent a large number of processes in different sectors, but face particular challenges in describing the individual and social behaviors that underpin climate change mitigation and adaptation. We assess descriptions of these behaviors in existing models, their commonalities and differences, and the uses to which they have been put. We find that behavioral models have a distinct and important role to play in climate research, but that they currently suffer from being strongly sectoral in nature, with agricultural models being the most common and behaviorally rich. There are also clear convergences, with economic-based decision-making remaining dominant and behaviors such as diffusion, interaction, anticipation, or learning remaining relatively neglected. Active climate change is also rarely modeled, with adaptation and mitigation generally represented as responses to economic drivers under static climatic conditions. Furthermore, dynamic behaviors, objectives, or decision-making processes are almost entirely absent, despite their clear relevance to climate change responses. We conclude that models have been more successful in the identification of important processes than in their implementation and that, while some behavioral processes may remain impossible to model, behavioral models of adaptation and mitigation in land-based sectors have substantial unexplored potential. We suggest that greater attention be paid to the cumulative coverage of models in this field, and that improvements in the representation of certain key behaviors be prioritized. WIREs Clim Change 2017, 8:e448. doi: 10.1002/wcc.448 For further resources related to this article, please visit the WIREs website.

Brown, C., S. Holzhauer, M. J. Metzger, J. S. Paterson and M. Rounsevell (2016). "Land managers’ behaviours modulate pathways to visions of future land systems." Regional Environmental Change: 1-15.

Attempts to influence the development of land systems are often based on detailed scenarios that constrain relevant factors, describe a range of divergent but plausible futures and identify potential pathways to visions of desirable conditions. However, a number of assumptions are usually made during this process, and one of the most substantial is that land managers display homogeneous, economically rational behaviour across space, time and scenarios. This assumption precludes the consideration of important behavioural effects and limits understanding of the feasibility of scenario-based pathways towards visions. We use an agent-based land use model to examine broad forms of behavioural variation within defined scenarios in theoretical contexts. We relate model results to stakeholder-developed visions of desired future land systems in Europe and so assess the scope for behavioural pathways towards these normative futures. We find that the achievability of visions is determined by internal inconsistencies, scenario conditions and the multifunctional potential of land uses, with a fundamental tension between large-scale land use productivity and small-scale diversity (i.e. land sparing and land sharing). Trading conditions affect this balance most strongly and represent an obvious target for governance strategies concerned with achieving multifunctional land use. However, within specific circumstances behavioural effects are strong and diverse, and can accelerate, counteract or mitigate the impacts of other drivers. This suggests that visions for the land system should focus on trade-offs, identifying those that are least strong, most acceptable and most susceptible to adjustment through behavioural or other influences.

Burkhard, B., M. Kandziora, Y. Hou and F. Müller (2014). "Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification." Landscape Online **34**(1): 1-32.

Burnham, M. and Z. Ma (2016). "Linking smallholder farmer climate change adaptation decisions to development." Climate and Development **8**(4): 289-311.

This paper synthesizes peer-reviewed literature on smallholders' adaptation to climate change in developing countries. The synthesis shows that multiple definitions of adaptation were used across studies, resulting in a conceptual murkiness that is a barrier to generalizing the findings to inform planned adaptation policies and projects. By using a seven-category typology to classify and compare smallholder farmer adaptations across communities, the synthesis shows that in order to reduce their vulnerability smallholder farmers have mostly taken action on environmental management and diversified their livelihoods through market exchange. Some have engaged in labour migration. Very few have pursued communal pooling, storage, or mobility as risk-reducing strategies. Despite the increasing recognition that adaptation is driven by multiple stressors, less than half of the adaptation studies included discussions of multiple stressors. The synthesis points to the need for (1) improved methodological clarity in climate change adaptation research, (2) more research on labour migration and climate change interactions, (3) more research to determine the conceptual and practical significance of communal pooling and storage as risk-reducing strategies, (4) the incorporation of the assessment of multiple stressors into climate change adaptation research and policy, and (5) more empirical research on what adaptive strategies are not adopted by smallholder farmers and why.

Burnham, M. and Z. Ma (2017). "Climate change adaptation: factors influencing Chinese smallholder farmers’ perceived self-efficacy and adaptation intent." Regional Environmental Change **17**(1): 171-186.

Burnham, M. and Z. Ma (2017). "Multi-Scalar Pathways to Smallholder Adaptation." World Development.

Smallholder farmers in the Loess Plateau Region of China are highly vulnerable to climate change. Effective adaptation governance requires in-depth, situated understanding of how adaptation is embedded in particular environmental, social, political, economic, and institutional contexts. Drawing on 93 qualitative interviews with smallholder households in five counties across three provinces on the Loess Plateau, we use a multi-scalar pathways approach to analyze two particular adaptations (planting maize and adopting drip irrigation). Our results show (1) how historical and ongoing multi-scalar, social–ecological processes interact to shape smallholder adaptation decision-making, leading to synergies, tensions, and contradictions across risk management domains and social institutions; (2) whether an adaptation strategy persists over time is in part determined by the extent to which the strategy allows smallholder households to manage various forms of risk and uncertainty in both the present and future; and (3) how past and ongoing multi-scalar adaptation pathways determine not only smallholder exposure to current stressors but also possible choices for future adaptation. Specifically, we find some smallholder adaptive strategies, such as planting maize, stabilize over time because they enable smallholders to manage market risk, climatic risk, and water pollution challenges, allow them to take advantage of opportunities to diversify their livelihoods through local wage work and labor migration, and, at the same time, fit the local social institutions that guide their agricultural management decisions. We also find some adaptive strategies promoted by non-local actors, such as drip irrigation, are abandoned because they create tensions with the ways smallholders construct their livelihoods to manage various forms of uncertainty and risk, and contradict the local social relations and cultural values embedded in their day-to-day lives. Together, these results provide insight into why particular smallholder adaptation pathways become stabilized and reproduced over time, and the cross-scalar environmental, social, political, economic, and institutional processes that underpin them.

Burnham, M., Z. Ma and B. Zhang (2016). "Making sense of climate change: hybrid epistemologies, socio‐natural assemblages and smallholder knowledge." Area **48**(1): 18-26.

This paper uses a mixed‐method approach to investigate smallholder perceptions of climate change in the Loess Plateau region of China. We combine qualitative and quantitative research methods with climate data analysis to gauge the climatic changes smallholders have perceived over the last 30 years, as well as how these changes have been experienced. At two research sites, each method produced markedly different results. Drawing on the work of feminist political ecologists and other geographers, we suggest that the dissonance between data sets generated using different research methods arises because each method produces knowledge that is partial and situated. To explain the contradictions between smallholder perceptions of climate change across the qualitative and quantitative methods and their disagreement with the climate record, we adopt aspects of assemblage theory and the dwelling perspective to suggest that smallholder knowledge of climate change is structured through their observations of and interactions with dynamic, networked socio‐natural assemblages. We argue that a better understanding of the conduits through which perceptions and experiences of climate change come into being, and hence how climate knowledge is shaped, is necessary to account for the multiple epistemologies through which climate change is known.

Carauta, M., E. Latynskiy, J. Mössinger, J. Gil, A. Libera, A. Hampf, L. Monteiro, M. Siebold and T. Berger (2017). "Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation." Regional Environmental Change: 1-12.

The need to balance agricultural production and environmental protection shifted the focus of Brazilian land-use policy toward sustainable agriculture. In 2010, Brazil established preferential credit lines to finance investments into low-carbon integrated agricultural systems of crop, livestock and forestry. This article presents a simulation-based empirical assessment of integrated system adoption in the state of Mato Grosso, where highly mechanized soybean–cotton and soybean–maize double-crop systems currently prevail. We employ bioeconomic modeling to explicitly capture the heterogeneity of farm-level costs and benefits of adoption. By parameterizing and validating our simulations with both empirical and experimental data, we evaluate the effectiveness of the ABC Integration credit through indicators such as land-use change, adoption rates and budgetary costs of credit provision. Alternative scenarios reveal that specific credit conditions might speed up the diffusion of low-carbon agricultural systems in Mato Grosso.

Chambers, R. and G. Conway (1992). Sustainable rural livelihoods: practical concepts for the 21st century, Institute of Development Studies (UK).

Cinner, J. (2018). "How behavioral science can help conservation." Science **362**(6417): 889-890.

Clarke, K. C. (2014). Cellular automata and agent-based models. Handbook of Regional Science. M. M. Fischer and P. Nijkamp. Berlin, Springer-Verlag**:** 1217-1233.

Clay, N. (2018). "Integrating livelihoods approaches with research on development and climate change adaptation." Progress in Development Studies **18**(1): 1-17.

This article advances theory and methods for integrating sustainable livelihoods approaches (SLAs) with assessments of adaptive capacity to climate change. The livelihoods concept has been inconsistently applied in research on human dimensions of global environmental change, resulting in limited understanding about how development programmes and policies influence adaptive capacity. Encouraging reflection on the conceptual and methodological overlaps of livelihoods and adaptation, I suggest a process-oriented approach to adaptation that centres on how adaptive capacity is unevenly shaped. Livelihoods analytical frameworks can help visualize complex adaptation pathways, illuminating how households and individuals come to differ in their capacities to adapt to climate change.

Colloff, M. J., B. Martín-López, S. Lavorel, B. Locatelli, R. Gorddard, P.-Y. Longaretti, G. Walters, L. van Kerkhoff, C. Wyborn, A. Coreau, R. M. Wise, M. Dunlop, P. Degeorges, H. Grantham, I. C. Overton, R. D. Williams, M. D. Doherty, T. Capon, T. Sanderson and H. T. Murphy (2017). "An integrative research framework for enabling transformative adaptation." Environmental Science & Policy **68**: 87-96.

Transformative adaptation will be increasingly important to effectively address the impacts of climate change and other global drivers on social-ecological systems. Enabling transformative adaptation requires new ways to evaluate and adaptively manage trade-offs between maintaining desirable aspects of current social-ecological systems and adapting to major biophysical changes to those systems. We outline such an approach, based on three elements developed by the Transformative Adaptation Research Alliance (TARA): (1) the benefits of adaptation services; that sub-set of ecosystem services that help people adapt to environmental change; (2) The values-rules-knowledge perspective (vrk) for identifying those aspects of societal decision-making contexts that enable or constrain adaptation and (3) the adaptation pathways approach for implementing adaptation, that builds on and integrates adaptation services and the vrk perspective. Together, these elements provide a future-oriented approach to evaluation and use of ecosystem services, a dynamic, grounded understanding of governance and decision-making and a logical, sequential approach that connects decisions over time. The TARA approach represents a means for achieving changes in institutions and governance needed to support transformative adaptation.

Costanza, R., R. de Groot, L. Braat, I. Kubiszewski, L. Fioramonti, P. Sutton, S. Farber and M. Grasso (2017). "Twenty years of ecosystem services: How far have we come and how far do we still need to go?" Ecosystem Services **28**: 1-16.

It has been 20years since two seminal publications about ecosystem services came out: an edited book by Gretchen Daily and an article in Nature by a group of ecologists and economists on the value of the world’s ecosystem services. Both of these have been very highly cited and kicked off an explosion of research, policy, and applications of the idea, including the establishment of this journal. This article traces the history leading up to these publications and the subsequent debates, research, institutions, policies, on-the-ground actions, and controversies they triggered. It also explores what we have learned during this period about the key issues: from definitions to classification to valuation, from integrated modelling to public participation and communication, and the evolution of institutions and governance innovation. Finally, it provides recommendations for the future. In particular, it points to the weakness of the mainstream economic approaches to valuation, growth, and development. It concludes that the substantial contributions of ecosystem services to the sustainable wellbeing of humans and the rest of nature should be at the core of the fundamental change needed in economic theory and practice if we are to achieve a societal transformation to a sustainable and desirable future.

Davies, J. and R. Bennett (2007). "Livelihood adaptation to risk: Constraints and opportunities for pastoral development in Ethiopia's Afar region." The Journal of Development Studies **43**(3): 490-511.

Abstract Development policies in the pastoral areas of Africa assume that pastoralists are poor. Using the Afar pastoralists of Ethiopia as the focus of research this article challenges this depiction of pastoralism by exploring pastoral livelihood goals and traditional strategies for managing risk. Investment in social institutions to minimise the risk of outright destitution, sometimes at the cost of increased poverty, and significant manipulation of local markets enable the Afar to exploit a highly uncertain and marginal environment. Improved development assistance and enhanced targeting of the truly vulnerable within pastoral societies demands an acceptance that pastoral poverty is neither uniform nor universal.

Development policies in the pastoral areas of Africa assume that pastoralists are poor. Using the Afar pastoralists of Ethiopia as the focus of research this article challenges this depiction of pastoralism by exploring pastoral livelihood goals and traditional strategies for managing risk. Investment in social institutions to minimise the risk of outright destitution, sometimes at the cost of increased poverty, and significant manipulation of local markets enable the Afar to exploit a highly uncertain and marginal environment. Improved development assistance and enhanced targeting of the truly vulnerable within pastoral societies demands an acceptance that pastoral poverty is neither uniform nor universal.

Daw, T. M., S. Coulthard, W. W. L. Cheung, K. Brown, C. Abunge, D. Galafassi, G. D. Peterson, T. R. McClanahan, J. O. Omukoto and L. Munyi (2015). "Evaluating taboo trade-offs in ecosystems services and human well-being." Proceedings of the National Academy of Sciences **112**(22): 6949-6954.

Managing ecosystems for multiple ecosystem services and balancing the well-being of diverse stakeholders involves different kinds of trade-offs. Often trade-offs involve noneconomic and difficult-to-evaluate values, such as cultural identity, employment, the well-being of poor people, or particular species or ecosystem structures. Although trade-offs need to be considered for successful environmental management, they are often overlooked in favor of win-wins. Management and policy decisions demand approaches that can explicitly acknowledge and evaluate diverse trade-offs. We identified a diversity of apparent trade-offs in a small-scale tropical fishery when ecological simulations were integrated with participatory assessments of social–ecological system structure and stakeholders’ well-being. Despite an apparent win-win between conservation and profitability at the aggregate scale, food production, employment, and well-being of marginalized stakeholders were differentially influenced by management decisions leading to trade-offs. Some of these trade-offs were suggested to be “taboo” trade-offs between morally incommensurable values, such as between profits and the well-being of marginalized women. These were not previously recognized as management issues. Stakeholders explored and deliberated over trade-offs supported by an interactive “toy model” representing key system trade-offs, alongside qualitative narrative scenarios of the future. The concept of taboo trade-offs suggests that psychological bias and social sensitivity may exclude key issues from decision making, which can result in policies that are difficult to implement. Our participatory modeling and scenarios approach has the potential to increase awareness of such trade-offs, promote discussion of what is acceptable, and potentially identify and reduce obstacles to management compliance.

Daw, T. M., C. C. Hicks, K. Brown, T. Chaigneau, F. A. Januchowski-Hartley, W. W. L. Cheung, S. Rosendo, B. Crona, S. Coulthard, C. Sandbrook, C. Perry, S. Bandeira, N. A. Muthiga, B. Schulte-Herbrüggen, J. Bosire and T. R. McClanahan (2016). "Elasticity in ecosystem services: exploring the variable relationship between ecosystems and human well-being." Ecology and Society **21**(2).

Although ecosystem services are increasingly recognized as benefits people obtain from nature, we still have a poor understanding of how they actually enhance multidimensional human well-being, and how well-being is affected by ecosystem change. We develop a concept of &#8220;ecosystem service elasticity&#8221; (ES elasticity) that describes the sensitivity of human well-being to changes in ecosystems. ES Elasticity is a result of complex social and ecological dynamics and is context dependent, individually variable, and likely to demonstrate nonlinear dynamics such as thresholds and hysteresis. We present a conceptual framework that unpacks the chain of causality from ecosystem stocks through flows, goods, value, and shares to contribute to the well-being of different people. This framework builds on previous conceptualizations, but places multidimensional well-being of different people as the final element. This ultimately disaggregated approach emphasizes how different people access benefits and how benefits match their needs or aspirations. Applying this framework to case studies of individual coastal ecosystem services in East Africa illustrates a wide range of social and ecological factors that can affect ES elasticity. For example, food web and habitat dynamics affect the sensitivity of different fisheries ecosystem services to ecological change. Meanwhile high cultural significance, or lack of alternatives enhance ES elasticity, while social mechanisms that prevent access can reduce elasticity. Mapping out how chains are interlinked illustrates how different types of value and the well-being of different people are linked to each other and to common ecological stocks. We suggest that examining chains for individual ecosystem services can suggest potential interventions aimed at poverty alleviation and sustainable ecosystems while mapping out of interlinkages between chains can help to identify possible ecosystem service trade-offs and winners and losers. We discuss conceptual and practical challenges of applying such a framework and conclude on its utility as a heuristic for structuring interdisciplinary analysis of ecosystem services and human well-being.

Deadman, P., D. T. Robinson, E. Moran and E. Brondizio (2004). "Colonist household decision-making and land use change in the Amazon Rainforest: an agent-based simulation." Environment and Planning B: Planning and Design **31**: 693-709.

Dou, Y. (2016). The impacts of cash transfer programs on rural livelihoods: a study of Caboclos in the Brazilian Amazon estuary region, UWSpace.

Dumrongrojwatthana, P., C. L. Page, N. Gajaseni and G. Trébuil (2011). "Co-constructing an agent-based model to mediate land use conflict between herders and foresters in northern Thailand." Journal of Land Use Science **6**(2-3): 101-120.

In conservation areas, land use conflicts frequently occur due to the increasing number of land resource managers and users who usually have different interests, objectives and perceptions. Sharing all these a priori legitimate differences is a prerequisite for better collective management of the land. The companion modelling approach is used to build a shared representation of interactions between vegetation dynamics, reforestation efforts and livestock grazing in a forest conservation area of northern Thailand. This article focuses on the participatory modelling process that led to the co-construction of an agent-based model. Sensitizing exercises on vegetation dynamics and an agent-based simulator associated with a role-playing game were the main tools used. The social interactions and decision-making processes observed during the gaming and simulation sessions were used to construct a set of rules implemented in a subsequent autonomous agent-based model. It will be used to simulate future land management scenarios with local stakeholders.

Eakin, H. C., M. C. Lemos and D. R. Nelson (2014). "Differentiating capacities as a means to sustainable climate change adaptation." Global Environmental Change **27**: 1-8.

There are two forms of capacity to adapt to global change: those associated with fundamental human development goals (generic capacity), and those necessary for managing and reducing specific climatic threats (specific). We argue that these two domains of capacity must be addressed explicitly, simultaneously and iteratively if climate change adaptation and sustainable development goals are to be attained. We propose a simple heuristic to understand the four main ways these two capacities interact, leading to more or less desirable outcomes. Drawing from three case studies of agricultural adaptation to climatic risk (Phoenix, AZ; Northeast Brazil; Chiapas, Mexico) we argue that the institutional context of adaptation can implicitly or explicitly undermine one form of capacity with repercussions for the development of the other. A better and more strategic balance of generic and specific capacities is needed if the promised synergies between sustainable development and adaptation are to be achieved.

Eakin, H. C., M. C. Lemos and D. R. Nelson (2014). "Differentiating capacities as a means to sustainable climate change adaptation." Global Environmental Change **27**: 1–8.

Eigenbrod, F., P. R. Armsworth, B. J. Anderson, A. Heinemeyer, S. Gillings, D. B. Roy, C. D. Thomas and K. J. Gaston (2010). "The impact of proxy-based methods on mapping the distribution of ecosystem services." Journal of Applied Ecology **47**(2): 377-385.

1.  An increasing number of studies are examining the distribution and congruence of ecosystem services, often with the goal of identifying areas that will provide multiple ecosystem service ‘hotspots’. However, there is a paucity of data on most ecosystem services, so proxies (e.g. estimates of a service for a particular land cover type) are frequently used to map their distribution. To date, there has been little attempt to quantify the effects of using proxies on distribution maps of ecosystem services, despite the potentially large errors associated with such data sets. 2.  Here, we provide the first study examining the effects of using proxies on ecosystem service maps and the degree of spatial congruence of these maps with primary data, using England as a case study. 3.  We show that land cover based proxies provide a poor fit to primary data surfaces for biodiversity, recreation and carbon storage, and that correlations between ecosystem services change depending on whether primary or proxy data are used for the analyses. 4.  The poor fit of proxies to primary data was also evident when we selected hotspots of single ecosystem services, and consistency between raw and modelled surfaces was extremely low when considering the locations that were coincident hotspots for multiple services. 5. Synthesis and applications. Proxies may be suitable for identifying broad-scale trends in ecosystem services, but even relatively good proxies are likely to be unsuitable for identifying hotspots or priority areas for multiple services.

Elsawah, S., J. H. A. Guillaume, T. Filatova, J. Rook and A. J. Jakeman (2015). "A methodology for eliciting, representing, and analysing stakeholder knowledge for decision making on complex socio-ecological systems: From cognitive maps to agent-based models." Journal of Environmental Management **151**: 500-516.

This paper aims to contribute to developing better ways for incorporating essential human elements in decision making processes for modelling of complex socio-ecological systems. It presents a step-wise methodology for integrating perceptions of stakeholders (qualitative) into formal simulation models (quantitative) with the ultimate goal of improving understanding and communication about decision making in complex socio-ecological systems. The methodology integrates cognitive mapping and agent based modelling. It cascades through a sequence of qualitative/soft and numerical methods comprising: (1) Interviews to elicit mental models; (2) Cognitive maps to represent and analyse individual and group mental models; (3) Time-sequence diagrams to chronologically structure the decision making process; (4) All-encompassing conceptual model of decision making, and (5) computational (in this case agent-based) Model. We apply the proposed methodology (labelled ICTAM) in a case study of viticulture irrigation in South Australia. Finally, we use strengths-weakness-opportunities-threats (SWOT) analysis to reflect on the methodology. Results show that the methodology leverages the use of cognitive mapping to capture the richness of decision making and mental models, and provides a combination of divergent and convergent analysis methods leading to the construction of an Agent Based Model.

Evans, T. P. and H. Kelley (2004). "Multi-scale analysis of a household level agent-based model of landcover change." J Environ Manage **72**(1-2): 57-72.

Scale issues have significant implications for the analysis of social and biophysical processes in complex systems. These same scale implications are likewise considerations for the design and application of models of landcover change. Scale issues have wide-ranging effects from the representativeness of data used to validate models to aggregation errors introduced in the model structure. This paper presents an analysis of how scale issues affect an agent-based model (ABM) of landcover change developed for a research area in the Midwest, USA. The research presented here explores how scale factors affect the design and application of agent-based landcover change models. The ABM is composed of a series of heterogeneous agents who make landuse decisions on a portfolio of cells in a raster-based programming environment. The model is calibrated using measures of fit derived from both spatial composition and spatial pattern metrics from multi-temporal landcover data interpreted from historical aerial photography. A model calibration process is used to find a best-fit set of parameter weights assigned to agents' preferences for different landuses (agriculture, pasture, timber production, and non-harvested forest). Previous research using this model has shown how a heterogeneous set of agents with differing preferences for a portfolio of landuses produces the best fit to landcover changes observed in the study area. The scale dependence of the model is explored by varying the resolution of the input data used to calibrate the model (observed landcover), ancillary datasets that affect land suitability (topography), and the resolution of the model landscape on which agents make decisions. To explore the impact of these scale relationships the model is run with input datasets constructed at the following spatial resolutions: 60, 90, 120, 150, 240, 300 and 480 m. The results show that the distribution of landuse-preference weights differs as a function of scale. In addition, with the gradient descent model fitting method used in this analysis the model was not able to converge to an acceptable fit at the 300 and 480 m spatial resolutions. This is a product of the ratio of the input cell resolution to the average parcel size in the landscape. This paper uses these findings to identify scale considerations in the design, development, validation and application of ABMs of landcover change.

Evans, T. P., K. Phanvilay, J. Fox and J. Vogler (2011). "An agent-based model of agricultural innovation, land-cover change and household inequality: the transition from swidden cultivation to rubber plantations in Laos PDR." Journal of Land Use Science **6**(2-3): 151-173.

This article examines the transition from shifting cultivation to rubber production for a study area in northern Laos PDR using an agent-based model of land-cover change. A primary objective of the model was to assess changes in household-level inequality with the transition from shifting cultivation to rubber adoption. A secondary objective was to develop explanations for the rate of rubber adoption in the study area. We fit the model to historical land-cover data and land use histories developed from household-level field interviews to reproduce the land use decisions of smallholders over time. The model results indicate an increase in household inequality over time as a function of the variable rate of rubber adoption over time.

Fairweather, J. (2010). "Farmer models of socio-ecologic systems: Application of causal mapping across multiple locations." Ecological Modelling **221**(3): 555-562.

Modelling ecological or environmental problems has potential to provide understanding of the causes of such problems and to indicate how to better manage them. Özesmi and Özesmi (2004) showed that cognitive or causal mapping can be used to develop maps of socio-ecological systems but these maps were based on stakeholders concerned with one ecosystem. This article shows how maps from a number of different dairy farmers in different locations, but each considering his or her own farm, can be used in meta analysis to make maps that represent how farmers think their farm ecosystem works. It also shows that the combination of causal mapping with the additional technique of Q method provides a useful solution to the practical problem of selecting from a sufficiently broad range of factors with potential to use in a map. Causal mapping in single or multiple locations contributes to the goal of using peoples’ knowledge of ecosystems to improve our understanding of socio-ecological systems.

Fedele, G., B. Locatelli and H. Djoudi (2017). "Mechanisms mediating the contribution of ecosystem services to human well-being and resilience." Ecosystem Services **28**(Part A): 43-54.

Human benefits from ecosystems result from complex interactions between ecological and social processes. People affect ecosystems’ capacity to deliver services that contribute to the well-being of humans and their resilience. The delivery of ecosystem services (ES) has often been considered asa linear and direct flow from nature to people without feedbacks or human inputs. We adjusted the widely used ES cascade to highlight how humans mediate each step in the ES delivery. We then applied the proposed framework to empirical field studies in Indonesia. We focused on the role of forested landscapes to increase rural people’s resilience to climate hazards such as drought and floods. We found that human actions determine benefits from ES through several mechanisms (ES management, mobilization, allocation-appropriation, and appreciation). These mechanisms are influenced by peoples’ decisions along the ES cascade, which depend on specific factors related to rules, assets, values, and spatial context. By facilitating or hindering ES flows, some stakeholders can determine who benefits from ES and influence the well-being of others. A better understanding of the mediating mechanisms, factors, and feedbacks in ES delivery can support the design of sound environmental assessments and sustainable land management practices.

Felipe-Lucia, M. R., B. Martín-López, S. Lavorel, L. Berraquero-Díaz, J. Escalera-Reyes and F. A. Comín (2015). "Ecosystem Services Flows: Why Stakeholders’ Power Relationships Matter." PLOS ONE **10**(7): e0132232.

The ecosystem services framework has enabled the broader public to acknowledge the benefits nature provides to different stakeholders. However, not all stakeholders benefit equally from these services. Rather, power relationships are a key factor influencing the access of individuals or groups to ecosystem services. In this paper, we propose an adaptation of the “cascade” framework for ecosystem services to integrate the analysis of ecological interactions among ecosystem services and stakeholders’ interactions, reflecting power relationships that mediate ecosystem services flows. We illustrate its application using the floodplain of the River Piedra (Spain) as a case study. First, we used structural equation modelling (SEM) to model the dependence relationships among ecosystem services. Second, we performed semi-structured interviews to identify formal power relationships among stakeholders. Third, we depicted ecosystem services according to stakeholders’ ability to use, manage or impair ecosystem services in order to expose how power relationships mediate access to ecosystem services. Our results revealed that the strongest power was held by those stakeholders who managed (although did not use) those keystone ecosystem properties and services that determine the provision of other services (i.e., intermediate regulating and final services). In contrast, non-empowered stakeholders were only able to access the remaining non-excludable and non-rival ecosystem services (i.e., some of the cultural services, freshwater supply, water quality, and biological control). In addition, land stewardship, access rights, and governance appeared as critical factors determining the status of ecosystem services. Finally, we stress the need to analyse the role of stakeholders and their relationships to foster equal access to ecosystem services.

Fernández-Giménez, M. E., G. R. H. Allington, J. Angerer, R. S. Reid, C. Jamsranjav, T. Ulambayar, K. Hondula, B. Baival, B. Batjav, T. Altanzul and Y. Baasandorj (2018). "Using an integrated social-ecological analysis to detect effects of household herding practices on indicators of rangeland resilience in Mongolia." Environmental Research Letters **13**(7): 075010.

Temperate grasslands, including those of northern Eurasia, are among the most imperiled ecosystems on Earth. Eighty percent of Mongolia’s land area is rangeland, where interacting climate, land-use and changes in governance threaten the sustainability of Mongolia’s rangelands and pastoral culture. Particularly concerning are the potential ecological impacts of changing pastoral grazing practices—namely declining use of grazing reserves and pastoral mobility. However, like other grazing practices globally, there have been no empirical studies to evaluate the effects of specific Mongolian grazing practices on ecological function at a management scale. We collected data on the grazing practices of 130 pastoral households across four ecological zones and sampled ecological conditions in their winter pastures. We used a novel social-ecological analysis process to (1) develop integrated, holistic indicators of ecological function using exploratory and confirmatory factor analysis, and (2) assess the effects of individual grazing practices on these indicators using statistical matching to control for confounding management and contextual factors. We identified two latent factors related to ecological and pastoral resilience: Factor 1 represents resource retention and soil stability and Factor 2 represents species richness and functional diversity. Using these two factors as response variables, we found that the values of both resilience factors were higher in pastures where households made fall or winter otor migrations or set aside grazing reserves. This study provides the first management-scale empirical test of the ecological response to specific grazing practices in Mongolia, using an approach that can be applied in other rangeland systems. Our findings highlight the importance to ecological and pastoral resilience of supporting traditional pastoral practices of mobility and grazing reserves, while also controlling stocking densities, increasing rangeland monitoring, and ensuring equitable access to state-designated emergency grazing reserves at local, regional, and national levels.

Filatova, T., P. H. Verburg, D. C. Parker and C. A. Stannard (2013). "Spatial agent-based models for socio-ecological systems: Challenges and prospects." Environmental Modelling & Software **45**: 1-7.

Foxon, T. J., J. Kohler, J. Michie and C. Oughton (2012). "Towards a new complexity economics for sustainability." Cambridge Journal of Economics **37**(1): 187-208.

Some of the most important and urgent topics requiring economic analysis and policy advice are the problems of climate change and environmental sustainability, and what can be done to alter corporate and individual behaviour to deal with these issues. Neoclassical economists tend to focus on market solutions such as carbon trading, drawing on ideas of perfect rationality of actors and the appropriateness of ‘marginal’ analysis. To link such policies to the whole range of potential actions, from legislative and regulatory to changing individual behaviours, requires the economy and society to be analysed in its full complexity, recognising that ‘marginal’ analysis can be not just irrelevant but positively harmful when the need is for systemic shifts in economic and social trajectories. This article draws upon a seminar series on complexity economics to consider how heterodox economic analysis can be brought to bear on the issue of the environment, to develop a realistic policy agenda for change.

Grimm, V. and S. F. Railsback (2012). "Pattern-oriented modelling: a ‘multi-scope’ for predictive systems ecology." Philosophical Transactions of the Royal Society B: Biological Sciences **367**(1586): 298-310.

Modern ecology recognizes that modelling systems across scales and at multiple levels—especially to link population and ecosystem dynamics to individual adaptive behaviour—is essential for making the science predictive. ‘Pattern-oriented modelling’ (POM) is a strategy for doing just this. POM is the multi-criteria design, selection and calibration of models of complex systems. POM starts with identifying a set of patterns observed at multiple scales and levels that characterize a system with respect to the particular problem being modelled; a model from which the patterns emerge should contain the right mechanisms to address the problem. These patterns are then used to (i) determine what scales, entities, variables and processes the model needs, (ii) test and select submodels to represent key low-level processes such as adaptive behaviour, and (iii) find useful parameter values during calibration. Patterns are already often used in these ways, but a mini-review of applications of POM confirms that making the selection and use of patterns more explicit and rigorous can facilitate the development of models with the right level of complexity to understand ecological systems and predict their response to novel conditions.

Groeneveld, J., B. Müller, C. M. Buchmann, G. Dressler, C. Guo, N. Hase, F. Hoffmann, F. John, C. Klassert, T. Lauf, V. Liebelt, H. Nolzen, N. Pannicke, J. Schulze, H. Weise and N. Schwarz (2017). "Theoretical foundations of human decision-making in agent-based land use models – A review." Environmental Modelling & Software **87**: 39-48.

Recent reviews stated that the complex and context-dependent nature of human decision-making resulted in ad-hoc representations of human decision in agent-based land use change models (LUCC ABMs) and that these representations are often not explicitly grounded in theory. However, a systematic survey on the characteristics (e.g. uncertainty, adaptation, learning, interactions and heterogeneities of agents) of representing human decision-making in LUCC ABMs is missing. Therefore, the aim of this study is to inform this debate by reviewing 134 LUCC ABM papers. We show that most human decision sub-models are not explicitly based on a specific theory and if so they are mostly based on economic theories, such as the rational actor, and mainly ignoring other relevant disciplines. Consolidating and enlarging the theoretical basis for modelling human decision-making may be achieved by using a structural framework for modellers, re-using published decision models, learning from other disciplines and fostering collaboration with social scientists.

Grothmann, T. and A. Patt (2005). "Adaptive capacity and human cognition: The process of individual adaptation to climate change." Global Environmental Change **15**(3): 199-213.

Adaptation has emerged as an important area of research and assessment among climate change scientists. Most scholarly work has identified resource constraints as being the most significant determinants of adaptation. However, empirical research on adaptation has so far mostly not addressed the importance of measurable and alterable psychological factors in determining adaptation. Drawing from the literature in psychology and behavioural economics, we develop a socio-cognitive Model of Private Proactive Adaptation to Climate Change (MPPACC). MPPACC separates out the psychological steps to taking action in response to perception, and allows one to see where the most important bottlenecks occur—including risk perception and perceived adaptive capacity, a factor largely neglected in previous climate change research. We then examine two case studies—one from urban Germany and one from rural Zimbabwe—to explore the validity of MPPACC to explaining adaptation. In the German study, we find that MPPACC provides better statistical power than traditional socio-economic models. In the Zimbabwean case study, we find a qualitative match between MPPACC and adaptive behaviour. Finally, we discuss the important implications of our findings both on vulnerability and adaptation assessments, and on efforts to promote adaptation through outside intervention.

Habib, T. J., S. Heckbert, J. J. Wilson, A. J. K. Vandenbroeck, J. Cranston and D. R. Farr (2016). "Impacts of land-use management on ecosystem services and biodiversity: an agent-based modelling approach." PeerJ **4**: e2814.

The science of ecosystem service (ES) mapping has become increasingly sophisticated over the past 20 years, and examples of successfully integrating ES into management decisions at national and sub-national scales have begun to emerge. However, increasing model sophistication and accuracy—and therefore complexity—may trade-off with ease of use and applicability to real-world decision-making contexts, so it is vital to incorporate the lessons learned from implementation efforts into new model development. Using successful implementation efforts for guidance, we developed an integrated ES modelling system to quantify several ecosystem services: forest timber production and carbon storage, water purification, pollination, and biodiversity. The system is designed to facilitate uptake of ES information into land-use decisions through three principal considerations: (1) using relatively straightforward models that can be readily deployed and interpreted without specialized expertise; (2) using an agent-based modelling framework to enable the incorporation of human decision-making directly within the model; and (3) integration among all ES models to simultaneously demonstrate the effects of a single land-use decision on multiple ES. We present an implementation of the model for a major watershed in Alberta, Canada, and highlight the system’s capabilities to assess a suite of ES under future management decisions, including forestry activities under two alternative timber harvest strategies, and through a scenario modelling analysis exploring different intensities of hypothetical agricultural expansion. By using a modular approach, the modelling system can be readily expanded to evaluate additional ecosystem services or management questions of interest in order to guide land-use decisions to achieve socioeconomic and environmental objectives.

Haines-Young, R., M. Potschin and F. Kienast (2012). "Indicators of ecosystem service potential at European scales: Mapping marginal changes and trade-offs." Ecological Indicators **21**: 39-53.

This study develops an approach to mapping indicators of the potential of ecosystems to supply ecosystem services, and the impact of changes in land cover and use upon them. The study focuses on the EU-25 plus Switzerland and Norway, and develops the methodology proposed by Kienast et al. (2009), which uses expert-and literature-driven modelling methods. The methods are explored in relation to mapping and assessing four of the ecosystem services: “Crop-based production”; “Wildlife products”; “Habitat diversity”; and “Recreation”. The potential to deliver services is assumed to be influenced by (a) land-use, (b) net primary production, and (c) bioclimatic and landscape properties such as mountainous terrain, adjacency to coastal and wetland ecosystems, as well as adjacency to landscape and nature protection zones. The novel aspect of this work is an analysis of whether the historical and the projected land use changes for the periods 1990–2000, 2000–2006, and 2000–2030 are likely to be supportive or degenerative in the capacity of ecosystems to deliver ecosystem services; we refer to these as ‘marginal’ or incremental changes. The latter are assessed by using land account data for 1990–2000 and 2000–2006 (LEAC, EEA, 2006) and EURURALIS 2.0 land use scenarios for 2000–2030. The results are reported at three spatial reporting units, i.e. (1) the NUTS-X regions, (2) the bioclimatic regions, and (3) the dominant landscape types. All mapped output has been compared with independently generated continent-wide assessments (maps of ecosystem services or environmental parameters/indicators), which revealed that the straightforward binary links work satisfactorily and generate plausible geographical patterns. This conclusion mainly holds for provisioning services. At the continental scale, the selected input parameters are thus valid proxies which can be used to assess the medium-term potential of landscapes to provide ecosystem services. For a subset of NUTS-x regions for which change trajectories for 1990–2000, 2000–2006 and 2000–2030 are available, trade-offs between the four services have been analyzed using cluster analyses. The latter allowed us to simultaneously analyze the state of the four services in year 2000 and the individual trajectories of each service over three time periods. As a result we obtained seven regions with distinct trade-off patterns. To our knowledge this is one of the first continental-wide analyses where land use trajectories are taken into account to construct an indicator to estimate the balance between a set or bundle of ecosystem services. The relationship between the outputs of this work and the development of rapid assessment and accounting frameworks is discussed.

Hainz-Renetzeder, C., A. Schneidergruber, M. Kuttner and T. Wrbka (2015). "Assessing the potential supply of landscape services to support ecological restoration of degraded landscapes: A case study in the Austrian-Hungarian trans-boundary region of Lake Neusiedl." Ecological Modelling **295**: 196-206.

The concept of ecosystem functions and services has increasingly gained attention in the scientific and political community in the last decade. Lot of work has been performed to assess the actual delivery of different services for society. Still, the reference of the landscape's potential to supply these actual services has not been investigated satisfactory so far. We thus aimed at assess the potential supply of landscape services in the study area of Lake Neusiedl in Austria – a region of acknowledged diversity and environmental quality – and compared these to the actual ones. We did this by setting up a map of constructed vegetation type where physiographic site conditions were used to calculate potential land cover in the area in GIS. These constructed vegetation types were linked to landscape services within a capacity matrix giving a weight between 0 (no supply) and 5 (high supply) to which amount one type can provide each single service. The resulting map showed large differences in areal extent of the different vegetation types reflecting the different landscapes in the region such as the dominance of forest steppe in the terraced landscapes or the occurrence of halophytic vegetation only in the lake basin. The same is true for the different landscape services. Some services like ‘nursery’ and ‘raw materials’ were quite highly provided throughout the area with values between 2.12 and 4.84, whereas ‘genetic resources’ and ‘pollination’ were only little provided (all values &lt;2). On the other hand, functions like ‘nutrient regulation’ or ‘refugium’ exhibited their large potential with values &gt;4 in the study area. The aggregation of the services by averaging values to finally derive three main service groups gave the highest values always to habitat (values between 3.1 and 4.8), followed by regulation (2.5–4.2) and then provision (1.9–3.2). Comparing the potential with the actual service supply, nearly all landscapes in the study area resulted in higher potential than the actual service supply. We further discuss possibilities to use the potential supply as a leitbild where restoration projects might be settled in the study area even though more detailed local data will be needed to set these projects up.

Heckbert, S., W. Adamowicz, P. Boxall and D. Hanneman (2009). Cumulative effects and emergent properties of multiple-use natural resources. International Workshop on Multi-Agent Systems and Agent-Based Simulation, Springer.

Hicks, C. C. and J. E. Cinner (2014). "Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs." Proceedings of the National Academy of Sciences **111**(50): 17791-17796.

Ecosystems provide a range of services that can benefit people. However, the extent to which people are able to harness those benefits depends not only on the supply of ecosystem services but also on their capacity to access them via a range of social, economic, and institutional mechanisms. Here, we examine how people perceive ecosystem service benefits across 28 coral reef fishing communities in four countries. We quantitatively show that bundles of benefits are mediated by key access mechanisms (e.g., rights-based, economic, knowledge, social, and institutional). Interestingly, social, institutional, and knowledge mechanisms were associated with the greatest number and diversity of benefits. Resource managers can focus on these access mechanisms to maximize ecosystem service benefits while minimizing human–environment impacts.Ecosystem services are supplied by nature but, by definition, are received by people. Ecosystem service assessments, intended to influence the decisions people make regarding their interactions with nature, need to understand how people benefit from different ecosystem services. A critical question is therefore, What determines the distribution of ecosystem service benefits between different sections of society? Here, we use an entitlements approach to examine how people perceive ecosystem service benefits across 28 coral reef fishing communities in four countries. In doing so, we quantitatively show that bundles of benefits are mediated by key access mechanisms (e.g., rights-based, economic, knowledge, social, and institutional). We find that specific access mechanisms influence which ecosystem services people prioritize. Social, institutional, and knowledge mechanisms are associated with the largest number and diversity of benefits. However, local context strongly determines whether specific access mechanisms enable or constrain benefits. Local ecological knowledge enabled people to prioritize a habitat benefit in Kenya, but constrained people from prioritizing the same benefit in Madagascar. Ecosystem service assessments, and their resultant policies, need to include the broad suite of access mechanisms that enable different people to benefit from a supply of ecosystem services.

Hicks, C. C., N. A. J. Graham and J. E. Cinner (2013). "Synergies and tradeoffs in how managers, scientists, and fishers value coral reef ecosystem services." Global Environmental Change **23**(6): 1444-1453.

Managing ecosystems in a changing environment faces the challenge of balancing diverse competing perspectives on which ecosystem services – nature's benefits – to prioritize. Consequently, we measured and compared how different stakeholders (managers, scientists and fishers) prioritize specific coral reef ecosystem services. Managers’ priorities were more aligned with scientists’ priorities but all stakeholder groups agreed that fishery, education, and habitat were high priorities. However, stakeholder groups differed in the extent to which they prioritized certain services. Fishers tended to assigned greater estimates to fishery and education, managers to culture, and scientists to coastal protection. Furthermore, using network analysis to map the interactions between stakeholders’ priorities, we found distinct synergies and trade-offs in how ecosystem services were prioritized, representing areas of agreement and conflict. In the fishers’ network, trade-offs emerged between two services, both of a higher priority, such as fishery and habitat. Conversely, in the scientists’ network, trade-offs emerged between services of a higher and lower priority, such as habitat and culture. The trade-offs and synergies that emerged in the managers’ network overlap with both fishers’ and scientists’ suggesting a potential brokering role that managers can play in balancing both priorities and conflicts. We suggest that measuring ecosystem service priorities can highlight key areas of agreement and conflict, both within and across stakeholder groups, to be addressed when communicating and prioritizing decisions.

Huber, F. K., Y. Yang, C. S. Weckerle and K. Seeland (2014). "Diversification of Livelihoods in a Society in Transition: A Case Study of Tibetan Communities in Southwest China." Society & Natural Resources **27**(7): 706-723.

In recent years, large development and market integration programs have altered the socioeconomic structures and cultural identity of rural communities and ethnic minorities in Southwest China and influenced the management of natural resources. This article analyzes livelihood strategies in the Shuiluo Valley, a remote area of the Sino-Tibetan borderlands. Agricultural activities and the management of natural resources were studied in five villages of Muli Tibetan Autonomous County, Sichuan Province. Characteristic for rural societies in transition, livelihoods were found to be flexible, combining subsistence agriculture, off-farm employment, and the exploitation of both renewable and nonrenewable natural resources. Accessibility of villages did not influence household income and livelihood activities, and poorer households were not found to depend more on natural resources or on income from agriculture than wealthier households. The option of gold prospecting constitutes a major difference compared to more nontimber forest product-based livelihoods in adjacent areas of Southwest China.

Huber, R., S. Briner, A. Peringer, S. Lauber, R. Seidl, A. Widmer, F. Gillet, A. Buttler, Q. B. Le and C. Hirschi (2013). "Modeling Social-Ecological Feedback Effects in the Implementation of Payments for Environmental Services in Pasture-Woodlands." Ecology and Society **18**(2).

An effective implementation of payment for environmental services (PES) must allow for complex interactions of coupled social-ecological systems. We present an integrative study of the pasture-woodland landscape of the Swiss Jura Mountains combining methods from natural and social sciences to explore feedback between vegetation dynamics on paddock level, farm-based decision making, and policy decisions on the national political level. Our modeling results show that concomitant climatic and socioeconomic changes advance the loss of open grassland in silvopastoral landscapes. This would, in the longer term, deteriorate the historical wooded pastures in the region, which fulfill important functions for biodiversity and are widely considered as landscapes that deserve protection. Payment for environmental services could counteract this development while respecting historical land-use and ecological boundary conditions. The assessed policy feedback process reveals that current policy processes may hinder the implementation of PES, even though a payment for the upkeep of wooded pasture would generally enjoy the backing of the relevant policy network. To effectively support the upkeep of the wooded pastures in the Jura, concomitant policy changes, such as market deregulation, must also be taken into account.

Iwamura, T., E. F. Lambin, K. M. Silvius, J. B. Luzar and J. M. V. Fragoso (2014). "Agent-based modeling of hunting and subsistence agriculture on indigenous lands: Understanding interactions between social and ecological systems." Environmental Modelling & Software **58**: 109-127.

Indigenous people of the Rupununi region of Amazonian Guyana interact with their natural environment through hunting and subsistence agriculture. To date the sustainability of indigenous livelihoods has been analyzed by modeling either hunting or forest clearing. Here we develop a holistic model framework with agent-based modeling to examine interactions between demographic growth, hunting, subsistence agriculture, land cover change, and animal population in the Rupununi. We use an extensive field dataset from social surveys, animal observation records and hunting kill locations along with satellite images. The model exhibits feedback loops between a growing human population and depletion of local natural resources. Our model can reproduce the population size of two different villages along with landscape patterns without further calibration. Our model can be used for understanding the conditions of sustainability for indigenous communities relying on subsistence agriculture and hunting, and for scenario analyses to examine the implications of external interventions.

Jones, K. W., S. Avila Foucat, E. C. Pischke, J. Salcone, D. Torrez, T. Selfa and K. E. Halvorsen (2019). "Exploring the connections between participation in and benefits from payments for hydrological services programs in Veracruz State, Mexico." Ecosystem Services **35**: 32-42.

Payments for hydrological services (PHS) programs are expected to confer tangible benefits to households. Impact evaluations of PHS programs, however, find few to no changes in material indicators. One reason for this may be that non-financial motivations and benefits—including environmental or social—influence participation and are important outcomes for households participating in PHS programs. In this paper we test this hypothesis using 56 interviews and 181 surveys from households in Veracruz State, Mexico. Using logistic regression models we find that human, natural, physical and financial capital are important to the decision to participate in PHS, but so are pro-social and pro-environmental motivations. Using counterfactual impact evaluation methods we find few changes in material benefits but do find that PHS participants are more likely to report positive changes in their household and community quality of life over the last five years compared to households not participating in PHS programs. Qualitative information supports these findings. Our results contribute to the evolving theory on PHS that participation is driven by a mix of financial and non-financial motivations and that non-material benefits are an important outcome of these programs.

Jorda-Capdevila, D., B. Rodríguez-Labajos and M. Bardina (2016). "An integrative modelling approach for linking environmental flow management, ecosystem service provision and inter-stakeholder conflict." Environmental Modelling & Software **79**: 22-34.

Fifteen water flow-dependent ecosystem services (ES) are modelled for the case of the Ter (Catalonia, Spain), a river with persisting intra- and inter-basin conflicts on water flows. The aim is to analyse ES response (and ensuing social reaction) to changes in water flow management, in a context of several tradeoffs and synergies driven by access to water use. We argue for a new modelling approach to integrate diverse values and perspectives through engaging with stakeholders' concerns and claims. This is done under different conditions, including droughts, wet years, and different options for managing flows. Our approach involves two stages, namely water allocation modelling, including scenario development, and ES provision modelling, including participatory design of service suitability curves. The method presented allows analysing spatial/temporal patterns and ES performance. The paper explains methodological innovation and its application to highlight the role of recurrent socio-environmental conflicts in water management decisions.

Kelly, R. A., A. J. Jakeman, O. Barreteau, M. E. Borsuk, S. ElSawah, S. H. Hamilton, H. J. Henriksen, S. Kuikka, H. R. Maier, A. E. Rizzoli, H. van Delden and A. A. Voinov (2013). "Selecting among five common modelling approaches for integrated environmental assessment and management." Environmental Modelling & Software **47**: 159-181.

The design and implementation of effective environmental policies need to be informed by a holistic understanding of the system processes (biophysical, social and economic), their complex interactions, and how they respond to various changes. Models, integrating different system processes into a unified framework, are seen as useful tools to help analyse alternatives with stakeholders, assess their outcomes, and communicate results in a transparent way. This paper reviews five common approaches or model types that have the capacity to integrate knowledge by developing models that can accommodate multiple issues, values, scales and uncertainty considerations, as well as facilitate stakeholder engagement. The approaches considered are: systems dynamics, Bayesian networks, coupled component models, agent-based models and knowledge-based models (also referred to as expert systems). We start by discussing several considerations in model development, such as the purpose of model building, the availability of qualitative versus quantitative data for model specification, the level of spatio-temporal detail required, and treatment of uncertainty. These considerations and a review of applications are then used to develop a framework that aims to assist modellers and model users in the choice of an appropriate modelling approach for their integrated assessment applications and that enables more effective learning in interdisciplinary settings.

Kennedy, C. M., P. L. Hawthorne, D. A. Miteva, L. Baumgarten, K. Sochi, M. Matsumoto, J. S. Evans, S. Polasky, P. Hamel, E. M. Vieira, P. F. Develey, C. H. Sekercioglu, A. D. Davidson, E. M. Uhlhorn and J. Kiesecker (2016). "Optimizing land use decision-making to sustain Brazilian agricultural profits, biodiversity and ecosystem services." Biological Conservation **204, Part B**: 221-230.

Designing landscapes that can meet human needs, while maintaining functioning ecosystems, is essential for long-term sustainability. To achieve this goal, we must better understand the trade-offs and thresholds in the provision of ecosystem services and economic returns. To this end, we integrate spatially explicit economic and biophysical models to jointly optimize agricultural profit (sugarcane production and cattle ranching), biodiversity (bird and mammal species), and freshwater quality (nitrogen, phosphorus, and sediment retention) in the Brazilian Cerrado. We generate efficiency frontiers to evaluate the economic and environmental trade-offs and map efficient combinations of agricultural land and natural habitat under varying service importance. To assess the potential impact of the Brazilian Forest Code (FC), a federal policy that aims to promote biodiversity and ecosystem services on private lands, we compare the frontiers with optimizations that mimic the habitat requirements in the region. We find significant opportunities to improve both economic and environmental outcomes relative to the current landscape. Substantial trade-offs between biodiversity and water quality exist when land use planning targets a single service, but these trade-offs can be minimized through multi-objective planning. We also detect non-linear profit-ecosystem services relationships that result in land use thresholds that coincide with the FC requirements. Further, we demonstrate that landscape-level planning can greatly improve the performance of the FC relative to traditional farm-level planning. These findings suggest that through joint planning for economic and environmental goals at a landscape-scale, Brazil's agricultural sector can expand production and meet regulatory requirements, while maintaining biodiversity and ecosystem service provision.

Kenny, D. C. (2017). "Modeling of natural and social capital on farms: Toward useable integration." Ecological Modelling **356**: 1-13.

In a world of increasing population and decreasing availability of arable land, the need to maintain and improve the quality of our farm systems is a clear and pressing one. Considerations of different types of capital give us a more holistic picture of what is at stake. Our decision-making mechanisms and tools must seek to integrate all types of capital, including natural and social capital, if we are to sustain long-term farm performance. Modeling is one way to integrate this ‘expanded’ notion of capital. While farm modeling is not a new concept, this paper reviews various types of models with the aims of determining which is most suitable to demonstrate the effect of natural and social capital on farm risk, farm resilience, and farm well-being. As an industry particularly vulnerable to extreme weather patterns and other ecological hazards, the concepts of risk and resilience are critical to sustain long-term farm well-being. Various types of farm models are covered in this review, including land use cover and change, agent-based, statistical, system dynamics, and participatory modeling. The paper also identifies key characteristics that assist in modeling the effects of natural and social capital management. I conclude that an integrated, spatially explicit, participatory, systems-based modeling process is suggested to usefully incorporate natural and social capital effects on farm risk, resilience, and well-being. This approach can incorporate a whole systems approach, capture system ‘leverage points’, and effectively involve affected stakeholders.

King, E. G., R. R. Unks and L. German (2018). "Constraints and capacities for novel livelihood adaptation: lessons from agricultural adoption in an African dryland pastoralist system." Regional Environmental Change **18**(5): 1403-1410.

Climate change, land use change, and sociopolitical and institutional transitions in African drylands have resulted in the loss, fragmentation, and degradation of environmental resources that pastoralists rely upon to sustain their livestock-based livelihoods. Diversification into irrigated agriculture is a potential strategy to increase food security. However, successful livelihood adaptation depends on access to key forms of natural, human, social, financial, and physical capitals, which may be lacking or unequally distributed in pastoralist communities. In two dryland pastoralist communities in Kenya, an international relief organization introduced irrigated farming in 2010. Nearly 200 individuals began farming, but within 4 years, all had quit. This study investigated the role of household access to different forms of capital in decisions to adopt agriculture, and how adaptive capacities, environmental conditions, and farming as a new livelihood practice interacted to shape household vulnerability. We found that decisions to farm were largely decoupled from access to assets that would afford greater adaptive capacity. The analysis also identified critical constraints that households encountered once they adopted farming. This study highlights the importance of more nuanced understandings of local capacities in the dynamics of adapting to environmental change. We recommend that prior to introducing interventions that promote new livelihood activities, development organizations should assess local capacities and pursue targeted strategies to increase household-level access to the forms of assets that will facilitate successful adaptation.

Koellner, T., A. Grét-Regamey, M. Marchamalo and R. Vignola (2008). Bayesian modeling of ecosystem services in human-environment systems. ACES 2008. A Conference on Ecosystem Services. Naples, Florida.

The adaptive management of ecosystem services requires knowledge about the

interdependence of land use decision-making and the ecosystem features in a

given landscape; and how this coupled humanenvironment system is influenced

by drivers of global change. The problem in this context is, that both decisionmaking

processes and the ecosystem changes are subject to large

uncertainties and incomplete information. Furthermore, trade-offs between

different ecosystem services and biodiversity exist and actors tend to maximize

only one feature. The adaptive management of an entire system thus needs to

find a solution, which optimizes all ecosystem services given uncertain

information.

For this purpose, we develop a Bayesian Network BN of the humanenvironment

system allowing evaluating simultaneously the effect of different

decision-making processes on ecosystem responses and updating the results

when better information becomes available.

We test the approach in a case study in the Swiss Alps, where we focus on

integrating the value of different ecosystem services as a support for landscape

planning. Results show that if uncertainties are not explicitly integrated into the

modeling framework, the information provided to the decision-makers might be

misleading.

For a case study in a Costa Rican watershed, we expand the BN with

exogenous drivers from market (e.g., change in price for crops), policy (e.g.,

change in national park border) and climate (e.g., change in frequency of heavy

rainfall). Policy instruments like command and control, park zoning and

payments for cosystem services can help reaching a more balanced

management of a watershed. For the planning of those instruments, however, it

is helpful to have a model which shows how the manager of individual land

units, takes policy measures, together with expected market changes and

climate change into account in his land use decision-making. For each

management unit, the prior probability of a specific land use and cover is

updated with a posterior probability, when additional information about the

management unit (e.g., slope, soil type, governance) is available.

This type of model can be used to plan and simulate new policy measures like

payments for ecosystem services, because it simultaneously takes the

ecosystem, socio-economic system and the policy system into account. The

model allows identifying management units with high and low values for each

ecosystem services and thus the targeting of available financial funds can be

optimized. First working steps show that such a BN provides a robust modeling

environment, useful for better informed and participatory decision-making.

Kok, M. T. J., K. Kok, G. D. Peterson, R. Hill, J. Agard and S. R. Carpenter (2017). "Biodiversity and ecosystem services require IPBES to take novel approach to scenarios." Sustainability Science **12**(1): 177-181.

What does the future hold for the world’s ecosystems and benefits that people obtain from them? While the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) has identified the development of scenarios as a key to helping decision makers identify potential impacts of different policy options, it currently lacks a long-term scenario strategy. IPBES will decide how it will approach scenarios at its plenary meeting on 22–28 February 2016, in Kuala Lumpur. IPBES now needs to decide whether it should create new scenarios that better explore ecosystem services and biodiversity dynamics. For IPBES to capture the social-ecological dynamics of biodiversity and ecosystem services, it is essential to engage with the great diversity of local contexts, while also including the global tele-coupling among local places. We present and compare three alternative scenario strategies that IPBES could use and then suggest a bottom-up, cross-scale scenario strategy to improve the policy relevance of future IPBES assessments. We propose five concrete steps as part of an effective, long term scenario development process for IPBES in cooperation with the scientific community.

Koniak, G., I. Noy-Meir and A. Perevolotsky (2011). "Modelling dynamics of ecosystem services basket in Mediterranean landscapes: a tool for rational management." Landscape Ecology **26**(1): 109-124.

Natural ecosystems are life-supporting systems providing diverse ecosystem services (ESs) and benefits to human societies: e.g., food and clean water, recreation opportunities or climate regulation. The contribution of natural and semi-natural ecosystems to the provision of such services depends to a large extent on vegetation structure and composition, which, in turn, change as a result of interactions between human decisions about land management, and spontaneous biological and environmental processes. Rational management of these dynamic ecosystems requires an ability to predict short- and long-term effects of management decisions on the desired ESs. The vegetation then contributes to, and modifies, the products and services obtained from the land. We applied mathematical modeling to study these complex relationships. We developed a model for a Mediterranean ecosystem which predicts the dynamics of multiple services in response to management scenarios, mediated by vegetation changes. Six representative ESs representing different groups were selected, based on available scientific information, for a detailed study: (1) density of geophytes, (2) potential contribution to honey production, (3) energy density of fleshy fruits foraged by birds, (4) forage for goats, (5) forage for cattle, and (6) carbon retention in woody plants. Mean contributions to each service by different vegetation cover types were estimated, and the overall service provided by the site was calculated as a weighted mean of these contributions. Services were measured in their appropriate units and subsequently standardized to a percentage of the maximum value observed in the study area. We attempted to combine all studied ESs, despite their different nature, into one “ESs basket”. This paper presents the dynamics of simulated vegetation composition and values of services in response to management scenarios involving grazing, fire and their combinations. Our approach can help land managers to evaluate alternative management scenarios by presenting the “services basket” obtained from the entire managed area.

Lamperti, F., A. Mandel, M. Napoletano, A. Sapio, A. Roventini, T. Balint and I. Khorenzhenko (2018). "Towards agent-based integrated assessment models: examples, challenges, and future developments." Regional Environmental Change.

Understanding the complex, dynamic, and non-linear relationships between human activities, the environment and the evolution of the climate is pivotal for policy design and requires appropriate tools. Despite the existence of different attempts to link the economy (or parts of it) to the evolution of the climate, results have often been disappointing and criticized. In this paper, we discuss the use of agent-based modeling for climate policy integrated assessment. First, we identify the main limitations of current mainstream models and stress how framing the problem from a complex system perspective might help, in particular when extreme climate conditions are at stake and general equilibrium effects are questionable. Second, we present two agent-based models that serve as prototypes for the analysis of coupled climate, energy, and macroeconomic dynamics. We argue that such models constitute examples of a promising approach for the integrated assessment of climate change and economic dynamics. They allow a bottom-up representation of climate damages and their cross-sectoral percolation, naturally embed distributional issues, and traditionally account for the role of finance in sustaining economic development and shaping the dynamics of energy transitions. All these issues are at the fore-front of the research in integrated assessment. Finally, we provide a careful discussion of testable policy exercises, modeling limitations, and open challenges for this stream of research. Notwithstanding great potential, there is a long way-to-go for agent-based models to catch-up with the richness of many existing integrated assessment models and overcome their major problems. This should encourage research in the area.

Le, Q. B., S. J. Park and P. L. G. Vlek (2010). "Land Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system: 2. Scenario-based application for impact assessment of land-use policies." Ecological Informatics **5**(3): 203-221.

Assessment of future socio-ecological consequences of land-use policies is useful for supporting decisions about what and where to invest for the best overall environmental and developmental outcomes. However, the task faces a great challenge due to the inherent complexity of coupled human–landscape systems and the long-term perspective required for sustainability assessment. Multi-agent system models have been recognized to be well suited to express the co-evolutions of the human and landscape systems in response to policy interventions. This paper applies the Land Use Dynamics Simulator (LUDAS) framework presented by Le et al. [Ecological Informatics 3 (2008) 135] to a mountain watershed in central Vietnam for supporting the design of land-use policies that enhance environmental and socio-economical benefits in long term. With an exploratory modelling strategy for complex integrated systems, our purpose is to assess relative impacts of policy interventions by measuring the long-term landscape and community divergences (compared with a baseline) driven from the widest plausible range of options for a given policy. Model's tests include empirical verification and validation of sub-models, rational evaluation of coupled model's structure, and behaviour tests using sensitivity/uncertainty analyses. We design experiments of replicated simulations for relevant policy factors in the study region that include (i) forest protection zoning, (ii) agricultural extension and (iii) agrochemical subsidies. As expected, the stronger human–environment interactions the performance indicators involve, the more uncertain the indicators are. Similar to the findings globally summarised by Liu et al. [Science 317 (2007) 1513], time lags between the implementation of land-use policies and the appearance of socio-ecological consequences are observed in our case. Long-term legacies are found in the responses of the total cropping area, farm size and income distribution to changes in forest protection zoning, implying that impact assessment of nature conservation policies on rural livelihoods must be considered in multiple decades. Our comparative assessment of alternative future socio-ecological scenarios shows that it is challenging to attain better either household income or forest conservation by straightforward expanding the current agricultural extensions and subsidy schemes without improving the qualities of the services. The results also suggest that the policy intervention that strengthens the enforcement of forest protection in the critical areas of the watershed and simultaneously create incentives and opportunities for agricultural production in the less critical areas will likely promote forest restoration and community income in long run. We also discuss limitations of the simulation model and recommend future directions for model development.

Le, Q. B., S. J. Park, P. L. G. Vlek and A. B. Cremers (2008). "Land-Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. I. Structure and theoretical specification." Ecological informatics **3**(2): 135-153.

Lopes, R. and N. Videira (2017). "Modelling feedback processes underpinning management of ecosystem services: The role of participatory systems mapping." Ecosystem Services **28**: 28-42.

Ecosystem services are dynamically interdependent. When conducting studies on ecosystem services valuation and assessment, the interdependencies and feedback structures underpinning ecosystem functioning should be identified and explicitly considered in management processes, especially when the goal is to pursue a plural and integrative approach that accounts for multiple values. This paper explores the role of a participatory system dynamics modelling approach – participatory systems mapping – as a tool to articulate different value dimensions of ecosystem services. The application of the tool is illustrated with a case study conducted in a protected area in Portugal, wherein inter-organisational stakeholder groups collaborated in the conceptualization of feedback processes characterizing ecosystem services during a group modelling workshop. The outcomes of the participatory workshop were submitted to a post-production process and returned to participants though an individual online survey aiming to validate the changes. Food production, recreation and ecotourism, biodiversity conservation and climate regulation were the ecosystem services explored. Results show that by accommodating the co-creation of causal system maps with stakeholders, the proposed approach fosters sharing of insights on the underlying cause–effect mechanisms and leverage points, supporting the identification of interrelationships between different ecosystem services and the selection of key indicators for management processes.

Malawska, A. and C. J. Topping (2016). "Evaluating the role of behavioral factors and practical constraints in the performance of an agent-based model of farmer decision making." Agricultural Systems **143**: 136-146.

Farmer decision making models often focus on the behavioral assumptions in the representation of the decision making, applying bounded rationality theory to shift away from the generally criticized profit maximizer approach. Although complex on the behavioral side, such representations are usually simplistic with respect to the available choice options in farmer decision making and practical constraints related to farming decisions. To ascertain the relevance of modeling different facets of farmer decision making, we developed an agent-based model of farmer decision making on crop choice, fertilizer and pesticide usage using an existing economic farm optimization model. We then gradually modified the model to include practical agronomic constraints and assumptions reflecting bounded rationality, and assessed the explanatory power of the added model components. The assessments were based on comparisons to the real world data and to the results of the previous model stages, and included two model versions differing with assumptions on the farmers' rationality. Thus, we assessed the sensitivity of the model to its behavioral assumptions. The results indicated that contrary to expectations, implementation of the practical constraints improved the model performance more than the modifications in the behavioral assumptions.

Malinga, R. (2016). Ecosystem services in agricultural landscapes: A study on farming and farmers in South Africa and Sweden, Stockholm Resilience Centre, Stockholm University.

Malinga, R., L. J. Gordon, R. Lindborg and G. Jewitt (2013). "Using Participatory Scenario Planning to Identify Ecosystem Services in Changing Landscapes." Ecology and Society **18**(4).

There is a growing interest in assessing ecosystem services to improve ecosystem management in landscapes containing a mix of different ecosystems. While methodologies for assessing ecosystem services are constantly improving, only little attention has been given to the identification of which ecosystem services to assess. Service selection is mostly based on current state of the landscape although many landscapes are both inherently complex and rapidly changing. In this study we examine whether scenario development, a tool for dealing with uncertainties and complexities of the future, gives important insights into the selection of ecosystem services in changing landscapes. Using an agricultural landscape in South Africa we compared different sets of services selected for an assessment by four different groups: stakeholders making the scenarios, experts who have read the scenarios, experts who had not read the scenarios, and services derived from literature. We found significant differences among the services selected by different groups, especially between the literature services and the other groups. Cultural services were least common in literature and that list was also most dissimilar in terms of identity, ranking, and numbers of services compared to the other three groups. The services selected by experts and the scenario stakeholders were relatively similar indicating that knowledge of a study area gained through the scenario exercise is not very different from that of experts actively working in the area. Although our results show limited value in using scenario development for improved ecosystem service selection per se, the scenario development process triggers important discussions with local and regional stakeholders about key issues of today, helping to more correctly assess changes in the future.

Malmborg, K., H. Sinare, E. Enfors Kautsky, I. Ouedraogo and L. J. Gordon (2018). "Mapping regional livelihood benefits from local ecosystem services assessments in rural Sahel." PLOS ONE **13**(2): e0192019.

Most current approaches to landscape scale ecosystem service assessments rely on detailed secondary data. This type of data is seldom available in regions with high levels of poverty and strong local dependence on provisioning ecosystem services for livelihoods. We develop a method to extrapolate results from a previously published village scale ecosystem services assessment to a higher administrative level, relevant for land use decision making. The method combines remote sensing (using a hybrid classification method) and interviews with community members. The resulting landscape scale maps show the spatial distribution of five different livelihood benefits (nutritional diversity, income, insurance/saving, material assets and energy, and crops for consumption) that illustrate the strong multifunctionality of the Sahelian landscapes. The maps highlight the importance of a diverse set of sub-units of the landscape in supporting Sahelian livelihoods. We see a large potential in using the resulting type of livelihood benefit maps for guiding future land use decisions in the Sahel.

Martin, R., A. Linstädter, K. Frank and B. Müller (2016). "Livelihood security in face of drought – Assessing the vulnerability of pastoral households." Environmental Modelling & Software **75**: 414-423.

Livestock grazing in drylands supports pastoral livelihoods but is facing multiple changes including shocks such as severe droughts. Herdsmen specifically cite drought events as a reason for the abandonment of their transhumance practices. The purpose of this study is to assess the relevance of drought as a driving force for losses of livelihood security leading to a specific systemic change – households abandoning transhumant pastoralism. We present and apply a framework for systematic analyses of the social–ecological functioning of pastoral resource use that consists of the following components: (1) A spatially-explicit social–ecological model for analyzing the system dynamics, especially in face of severe drought in connection with other driving forces of variability, (2) an operationalized measure for assessing livelihood security, and (3) a strategy for systematic vulnerability assessments of pastoral households by scenario comparison. This approach is applied to the land use system of the transhumant pastoralists in the High Atlas Mountains of Morocco. The results indicate that drought is the main threat to livelihood security in only a few cases, eventually forcing households to abandon their transhumant lifestyle. Instead, other (endogenous and exogenous) sources of variability were found to be the main driving force for vulnerability, depending on the household characteristics such as income needs and the level of pastoral mobility. We discuss implications on the role of severe drought in connection with other processes of global change such as social change and land use change for livelihood security in pastoral systems. Moreover, on the basis of these findings, we discuss how the relevance of shocks as a driving force of systemic changes in coupled human-nature-systems may be adequately explored. These conclusions concern the interplay of exogenous and endogenous factors, and unintended side-effects of intended changes.

Martin, R. and M. Schlüter (2015). "Combining system dynamics and agent-based modeling to analyze social-ecological interactions—an example from modeling restoration of a shallow lake." Frontiers in Environmental Science **3**(66).

Modeling social-ecological interactions between humans and ecosystems to analyze their implications for sustainable management of social-ecological systems (SES) has multiple challenges. When integrating social and ecological dynamics, which are often studied separately, one has to deal with different modeling paradigms, levels of analysis, temporal and spatial scales and data availabilities in the social and ecological domains. A major challenge, for instance, is linking the emergent patterns from individual micro-level human decisions to system level processes such as reinforcing feedbacks determining the state of the ecosystem. We propose building a hybrid model that combines a system dynamics with an agent-based approach to address some of these challenges. In particular, we present a procedure for model development and analysis that successively builds up complexity and understanding of model dynamics, particular with respect to feedbacks between the social and ecological system components. The proposed steps allow for a systematic increase of the coupling between the submodels and building confidence in the model before deploying it to study the coupled dynamics. The procedure consists of steps for i) specifying the characteristics of the link between the social and ecological systems, ii) validating the decoupled submodels, iii) doing sensitivity analysis of the decoupled submodels with respect to the drivers from the respective other subsystem and, finally iii) analyzing the coupled model. We illustrate the procedure and discuss opportunities and limitations of hybrid models against the background of an archetypical SES case study, namely the restoration of a turbid lake. Our approach exemplifies how a hybrid model is used to unpack SES complexity and analyze interactions between ecological dynamics and micro-level human actions. We discuss the benefits and challenges of combining a system dynamics models as an aggregated view with an agent-based model as a disaggregated view to improve social-ecological system understanding.

Martinez-Harms, M. J., B. A. Bryan, P. Balvanera, E. A. Law, J. R. Rhodes, H. P. Possingham and K. A. Wilson (2015). "Making decisions for managing ecosystem services." Biological Conservation **184**(Supplement C): 229-238.

Numerous assessments have quantified, mapped, and valued the services provided by ecosystems that are important for human wellbeing. However, much of the literature does not clarify how the information gathered in such assessments could be used to inform decisions that will impact ecosystem services. We propose that the process of making management decisions for ecosystem services comprises five core steps: identification of the problem and its social–ecological context; specification of objectives and associated performance measures; defining alternative management actions and evaluating the consequences of these actions; assessment of trade-offs and prioritization of alternative management actions; and making management decisions. We synthesize the degree to which the peer-reviewed ecosystem services literature has captured these steps. For the ecosystem service paradigm to gain traction in science and policy arenas, future ecosystem service assessments should have clearly articulated objectives, seek to evaluate the consequences of alternative management actions, and facilitate closer engagement between scientists and stakeholders.

Martinez-Harms, M. J., S. Gelcich, R. M. Krug, F. J. F. Maseyk, H. Moersberger, A. Rastogi, G. Wambugu, C. B. Krug, E. M. Spehn and U. Pascual (2018). "Framing natural assets for advancing sustainability research: translating different perspectives into actions." Sustainability Science **13**(6): 1519-1531.

Sustainability is a key challenge for humanity in the context of complex and unprecedented global changes. Future Earth, an international research initiative aiming to advance global sustainability science, has recently launched knowledge–action networks (KANs) as mechanisms for delivering its research strategy. The research initiative is currently developing a KAN on “natural assets” to facilitate and enable action-oriented research and synthesis towards natural assets sustainability. ‘Natural assets’ has been adopted by Future Earth as an umbrella term aiming to translate and bridge across different knowledge systems and different perspectives on peoples’ relationships with nature. In this paper, we clarify the framing of Future Earth around natural assets emphasizing the recognition on pluralism and identifying the challenges of translating different visions about the role of natural assets, including via policy formulation, for local to global sustainability challenges. This understanding will be useful to develop inter-and transdisciplinary solutions for human–environmental problems by (i) embracing richer collaborative decision processes and building bridges across different perspectives; (ii) giving emphasis on the interactions between biophysical and socioeconomic drivers affecting the future trends of investments and disinvestments in natural assets; and (iii) focusing on social equity, power relationships for effective application of the natural assets approach. This understanding also intends to inform the scope of the natural asset KAN’s research agenda to mobilize the translation of research into co-designed action for sustainability.

Matthews, R. (2006). "The People and Landscape Model (PALM): Towards full integration of human decision-making and biophysical simulation models." Ecological Modelling **194**(4): 329-343.

Matthews, R. B., N. G. Gilbert, A. Roach, J. G. Polhill and N. M. Gotts (2007). "Agent-based land-use models: a review of applications." Landscape Ecology **22**(10): 1447-1459.

Agent-based modelling is an approach that has been receiving attention by the land use modelling community in recent years, mainly because it offers a way of incorporating the influence of human decision-making on land use in a mechanistic, formal, and spatially explicit way, taking into account social interaction, adaptation, and decision-making at different levels. Specific advantages of agent-based models include their ability to model individual decision-making entities and their interactions, to incorporate social processes and non-monetary influences on decision-making, and to dynamically link social and environmental processes. A number of such models are now beginning to appear—it is timely, therefore, to review the uses to which agent-based land use models have been put so far, and to discuss some of the relevant lessons learnt, also drawing on those from other areas of simulation modelling, in relation to future applications. In this paper, we review applications of agent-based land use models under the headings of (a) policy analysis and planning, (b) participatory modelling, (c) explaining spatial patterns of land use or settlement, (d) testing social science concepts and (e) explaining land use functions. The greatest use of such models so far has been by the research community as tools for organising knowledge from empirical studies, and for exploring theoretical aspects of particular systems. However, there is a need to demonstrate that such models are able to solve problems in the real world better than traditional modelling approaches. It is concluded that in terms of decision support, agent-based land-use models are probably more useful as research tools to develop an underlying knowledge base which can then be developed together with end-users into simple rules-of-thumb, rather than as operational decision support tools.

Mehring, M., U. Zajonz and D. Hummel (2017). "Social-Ecological Dynamics of Ecosystem Services: Livelihoods and the Functional Relation between Ecosystem Service Supply and Demand—Evidence from Socotra Archipelago, Yemen and the Sahel Region, West Africa." Sustainability **9**(7): 1037.

Meyfroidt, P. (2013). "Environmental cognitions, land change, and social–ecological feedbacks: an overview." Journal of Land Use Science **8**(3): 341-367.

Understanding land use transitions requires analyzing how, when facing qualitative environmental change, human agents may modify their beliefs, values, and decision rules. This article first reviews some of the useful theories analyzing how environmental change can have a feedback effect on behaviors, via the environmental cognitions. Then, it discusses three propositions for more cognitively realistic agents in land change science: (i) land use choices result from multiple decision-making processes and rely on various motives, influenced by social norms, emotions, beliefs, and values toward the environment; (ii) social?ecological feedbacks are mediated by the environmental cognitions, that is, the perception, interpretation, evaluation of environmental change, and decision-making; (iii) human agents actively re-evaluate their beliefs, values, and functioning to adapt to unexpected environmental changes. Empirical and modeling studies in land change science can progress by linking the three components of the feedback loop, that is, environmental changes, environmental cognitions, and land use practices.

Mialhe, F., N. Becu and Y. Gunnell (2012). "An agent-based model for analyzing land use dynamics in response to farmer behaviour and environmental change in the Pampanga delta (Philippines)." Agriculture, Ecosystems & Environment **161**: 55-69.

Agent-based models (ABMs) are increasingly employed to understand land use change in agro-ecosystems. Here we use an ABM named CHANOS to capture how a range of variables influences decision-making processes among farmers with respect to their choice of cropping system, and to analyze the resulting changes in land use patterns. The model is experimental but is empirically based and nourished by field data acquired in the Pampanga delta, Philippines, where rice cropping and aquaculture have been competing over the last 40 years at the expense of natural habitats. Among the variables we include agent behavioural profiles but also forcing factors relevant to the natural, economic and political settings of the system: e.g. continuous (deltaic land subsidence) and discrete (typhoon events) environmental processes, external market forces, and changes in government-driven agricultural policies. Assessing the relative weights of these factors was performed through a detailed analysis of decisional outcomes. The farmers fall into three behavioural categories: rational, collective minded and boundedly rational. Likewise, four different environmental dynamics are driven respectively by no deltaic subsidence, steady subsidence, accelerating subsidence, and subsidence punctuated by additional external variables such as listed above. Twelve scenarios were elaborated by combining the agent behaviour algorithms with the environmental dynamics. Results reveal three categories of land-use change: an extension of paddy over natural habitat, of aquaculture over natural habitat and paddy, and a succession of periods alternating between paddy and aquaculture. Several indicators show that the rational agents are the most reactive and adaptive to environmental changes. Collective-minded agents act independently from environmental changes. Their ability to cope with change is limited and adaptations take longer to propagate. Boundedly rational agents reveal adaptive capacities but are less reactive than rational agent. CHANOS thus provides a dynamic tool for understanding the social fabric and behavioural processes behind land use change.

Miyasaka, T., Q. B. Le, T. Okuro, X. Zhao and K. Takeuchi (2017). "Agent-based modeling of complex social–ecological feedback loops to assess multi-dimensional trade-offs in dryland ecosystem services." Landscape Ecology **32**(4): 707-727.

Recent conceptual developments in ecosystem services research have revealed the need to elucidate the complex and unintended relationships between humans and the environment if we are to better understand and manage ecosystem services in practice.

Murray-Rust, D., C. Brown, J. van Vliet, S. J. Alam, D. T. Robinson, P. H. Verburg and M. Rounsevell (2014). "Combining agent functional types, capitals and services to model land use dynamics." Environmental Modelling & Software **59**: 187-201.

Models of land use change are becoming increasingly complex as they attempt to explore the effects of climatic, political, economic and demographic change on land systems and the services these systems produce. ‘Bottom-up’ agent based models are a useful method for exploring the effects of local processes and human behaviour, but are generally limited to small spatial scales due to the complex parameterisations involved. Conversely, ‘top-down’ land allocation models can be applied at large spatial scales, but are less adept at accounting for human behaviour and non-economic factors such as the supply of ecosystem services. Models that combine the strengths of these two approaches are required for the advancement of land use science. Here, we present an agent based land use modelling framework designed to be run over large spatial extents and to be capable of accounting for relevant forms of human behaviour, variations in land use intensities, multifunctional ecosystem service production and the actions of institutions that affect land use change. We give a full description of this framework, called CRAFTY (Competition for Resources between Agent Functional TYpes), and provide details of how it can be applied and extended, including some simple examples of its ability to model important processes of land use change. These include changes in demand for and supply of ecosystem services, variation in land use intensity and multi-functionality, and heterogeneous behaviour amongst land managers.

Murray-Rust , D., N. Dendoncker, T. P. Dawson, L. Acosta-Michlik, E. Karali, E. Guillem and M. Rounsevell (2011). "Conceptualising the analysis of socio-ecological systems through ecosystem services and agent-based modelling." Journal of Land Use Science **6**(2-3): 83-99.

In this article we present a conceptual model for analysing socio-economic systems using agent-based modelling, with ecosystem services as the focus of analysis. This is designed to allow the development of integrated models of human land managers, the landscapes which they manage and certain species of interest which live in these landscapes. We argue that in order to understand the effect of humans on the landscape and ES provision, we must take into account the preferences and priorities which they have; it is necessary to firmly embed their models into a rich socio-ecological model context, while taking into account the idiosyncrasies of human decision making. This requires a rich representation of plant and animal responses to human actions, in order to provide dynamic feedback on the results of courses of action and move beyond the static indicator frameworks commonly used. After exploring possible implementations of parts of the conceptual model, we conclude that it will provide a useful tool for analysing the effects of human behaviour on ecosystem services.

Murray-Rust, D., D. T. Robinson, E. Guillem, E. Karali and M. Rounsevell (2014). "An open framework for agent based modelling of agricultural land use change." Environmental Modelling & Software **61**: 19-38.

There is growing interest in creating empirically grounded agent based models (ABMs) to simulate land use change at a variety of spatio-temporal scales. The development of land use change models is challenging, as there is a need to connect representations of human behavioural processes to simulations of the biophysical environment. This paper presents a new agent-based modelling framework (Aporia) that has the goal of reducing the complexity and difficulty of constructing high-fidelity land use models. Building on earlier conceptual developments for modelling land use change and the provision of ecosystem services, Aporia was designed to be modular, flexible and open, using a declarative, compositional approach to create complex models from subcomponents. The framework can be tightly or loosely coupled with multiple vegetation models, it can be set up to evaluate a range of ecosystem service indicators, and it can be calibrated for a range of different landscape-scale case studies and modelling styles. The framework is released under an Open Source licence, and can be freely re-used and modified to form the basis of new models. We illustrate this with two case studies implemented using Aporia, exploring different socio-economic scenarios and behavioural characteristics on the land use decisions of Swiss and Scottish farmers. We also discuss the benefits of frameworks in terms of their flexibility, expandability, verification and transparency.

Olabisi, L. S., R. Q. Wang and A. Ligmann-Zielinska (2015). "Why Don’t More Farmers Go Organic? Using A Stakeholder-Informed Exploratory Agent-Based Model to Represent the Dynamics of Farming Practices in the Philippines." Land **4**(4): 979-1002.

Outeiro, L., E. Ojea, J. Garcia Rodrigues, A. Himes-Cornell, A. Belgrano, Y. Liu, E. Cabecinha, C. Pita, G. Macho and S. Villasante (2017). "The role of non-natural capital in the co-production of marine ecosystem services." International Journal of Biodiversity Science, Ecosystem Services & Management **13**(3): 35-50.

ABSTRACTA growing concern is arising to recognize that ecosystem services (ES) production often requires the integration of non-natural capital with natural capital in a process known as co-production. Several studies explore co-production in different terrestrial ecosystems, such as agriculture or water delivery, but less attention has been paid to marine ecosystems. Coastal activities such as aquaculture, shellfish harvesting, and small-scale fishing deliver important benefits for seafood provision, but are also inextricably linked to cultural and recreational ES. The degree to which co-production can determine the provision of ES in marine systems has yet not been explored. This paper addresses this key topic with an exploratory analysis of case studies where marine ES are co-produced. We look at five small-scale fisheries that range from intensive semi-aquaculture in Galicia (Spain), to wild harvesting in Northern Portugal, and discuss to what extent co-production influences ES delivery. We find that a direct relationship exists between co-production level and ES delivery in the case of provisioning ES (e.g., fish harvest), but not necessarily in the delivery of other ES. We also find that management practices and property regimes may be affecting trade-offs between co-production and ES.

Palomo, I., M. R. Felipe-Lucia, E. M. Bennett, B. Martín-López and U. Pascual (2016). "Chapter six-disentangling the pathways and effects of ecosystem service co-production." Advances in Ecological Research **54**: 245-283.

Palomo, I., M. R. Felipe-Lucia, E. M. Bennett, B. Martín-López and U. Pascual (2016). Chapter Six - Disentangling the Pathways and Effects of Ecosystem Service Co-Production. Advances in Ecological Research. G. Woodward and D. A. Bohan, Academic Press. **54:** 245-283.

Abstract Research on ecosystem services has become a dominant field within environmental management, framing the way in which human–nature relationships are understood and managed. Although ecosystem services are usually defined as ‘the benefits that humans receive from nature’, our work shows that most services are actually co-produced by a mixture of natural capital and various forms of social, human, financial and technological capital. Here, we review how ecosystem services are co-produced, and then we assess how this affects the quantity, quality, trade-offs, resilience and the equity of the distribution of ecosystem services. Then we discuss the implications of co-production for sustainability. Finally, we present some challenges for an adequate consideration of co-production within the assessment of ecosystem services.

Parker, D. C., A. Hessl and S. C. Davis (2008). "Complexity, land-use modeling, and the human dimension: Fundamental challenges for mapping unknown outcome spaces." Geoforum **39**(2): 789-804.

Land-use systems are characterized by complex interactions between human decision-makers and their biophysical environment. Mismatches between the scale of human drivers and the impacts of human decisions potentially threaten the ecological sustainability of these systems. This article reviews sources of complexity in land-use systems, moving from the human decision level to human interactions to effects over space, time and scale. Selected challenges in modeling such systems and potential resolutions are discussed, including strategies to empiricize complex models and methods for linking models across human and natural systems. Illustrative examples from published literature and an ongoing research project focused on timber harvest and carbon sequestration are used throughout the paper. The paper concludes with a brief discussion of remaining challenges to modeling indirect and cross-scale linkages and of the potential utility of complex models of land systems.

Parker, D. C., S. M. Manson, M. A. Janssen, M. J. Hoffmann and P. Deadman (2003). "Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review." Annals of the Association of American Geographers **93**(2): 314-337.

Abstract This article presents an overview of multi-agent system models of land-use/cover change (MAS/LUCC models). This special class of LUCC models combines a cellular landscape model with agent-based representations of decision making, integrating the two components through specification of interdependencies and feedbacks between agents and their environment. The authors review alternative LUCC modeling techniques and discuss the ways in which MAS/LUCC models may overcome some important limitations of existing techniques. We briefly review ongoing MAS/LUCC modeling efforts in four research areas. We discuss the potential strengths of MAS/LUCC models and suggest that these strengths guide researchers in assessing the appropriate choice of model for their particular research question. We find that MAS/LUCC models are particularly well suited for representing complex spatial interactions under heterogeneous conditions and for modeling decentralized, autonomous decision making. We discuss a range of possible roles for MAS/LUCC models, from abstract models designed to derive stylized hypotheses to empirically detailed simulation models appropriate for scenario and policy analysis. We also discuss the challenge of validation and verification for MAS/LUCC models. Finally, we outline important challenges and open research questions in this new field. We conclude that, while significant challenges exist, these models offer a promising new tool for researchers whose goal is to create fine-scale models of LUCC phenomena that focus on human-environment interactions.

This article presents an overview of multi-agent system models of land-use/cover change (MAS/LUCC models). This special class of LUCC models combines a cellular landscape model with agent-based representations of decision making, integrating the two components through specification of interdependencies and feedbacks between agents and their environment. The authors review alternative LUCC modeling techniques and discuss the ways in which MAS/LUCC models may overcome some important limitations of existing techniques. We briefly review ongoing MAS/LUCC modeling efforts in four research areas. We discuss the potential strengths of MAS/LUCC models and suggest that these strengths guide researchers in assessing the appropriate choice of model for their particular research question. We find that MAS/LUCC models are particularly well suited for representing complex spatial interactions under heterogeneous conditions and for modeling decentralized, autonomous decision making. We discuss a range of possible roles for MAS/LUCC models, from abstract models designed to derive stylized hypotheses to empirically detailed simulation models appropriate for scenario and policy analysis. We also discuss the challenge of validation and verification for MAS/LUCC models. Finally, we outline important challenges and open research questions in this new field. We conclude that, while significant challenges exist, these models offer a promising new tool for researchers whose goal is to create fine-scale models of LUCC phenomena that focus on human-environment interactions.

Pascual, U., P. Balvanera, S. Díaz, G. Pataki, E. Roth, M. Stenseke, R. T. Watson, E. Başak Dessane, M. Islar, E. Kelemen, V. Maris, M. Quaas, S. M. Subramanian, H. Wittmer, A. Adlan, S. Ahn, Y. S. Al-Hafedh, E. Amankwah, S. T. Asah, P. Berry, A. Bilgin, S. J. Breslow, C. Bullock, D. Cáceres, H. Daly-Hassen, E. Figueroa, C. D. Golden, E. Gómez-Baggethun, D. González-Jiménez, J. Houdet, H. Keune, R. Kumar, K. Ma, P. H. May, A. Mead, P. O’Farrell, R. Pandit, W. Pengue, R. Pichis-Madruga, F. Popa, S. Preston, D. Pacheco-Balanza, H. Saarikoski, B. B. Strassburg, M. van den Belt, M. Verma, F. Wickson and N. Yagi (2017). "Valuing nature’s contributions to people: the IPBES approach." Current Opinion in Environmental Sustainability **26-27**(Supplement C): 7-16.

Nature is perceived and valued in starkly different and often conflicting ways. This paper presents the rationale for the inclusive valuation of nature’s contributions to people (NCP) in decision making, as well as broad methodological steps for doing so. While developed within the context of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), this approach is more widely applicable to initiatives at the knowledge–policy interface, which require a pluralistic approach to recognizing the diversity of values. We argue that transformative practices aiming at sustainable futures would benefit from embracing such diversity, which require recognizing and addressing power relationships across stakeholder groups that hold different values on human nature-relations and NCP.

Potschin-Young, M., R. Haines-Young, C. Görg, U. Heink, K. Jax and C. Schleyer (2017). "Understanding the role of conceptual frameworks: Reading the ecosystem service cascade." Ecosystem Services.

The aim of this paper is to identify the role of conceptual frameworks in operationalising and mainstreaming the idea of ecosystem services. It builds on some initial discussions from IPBES, which suggested that conceptual frameworks could be used to: ‘simplify thinking’, ‘structure work’, ‘clarify issues’, and ‘provide a common reference point’. The analysis uses the cascade model as a focus and looks at the way it has been used in recent published material and across a set of case studies from the EU-funded OpenNESS Project as a device for conceptual framing. It found that there are examples in the literature that show the cascade model indeed being used as an ‘organising framework’, a tool for ‘re-framing’ perspectives, an ‘analytical template’, and as an ‘application framework’. Although the published materials on the cascade are rich, these accounts lack insights into the process by which the different versions of the model were created, and so we turned to the set of OpenNESS case studies to examine how they read the cascade. We found that the cascade was able to provide a common reference for a diverse set of studies, and that it was sufficiently flexible for it to be developed and elaborated in ways that were meaningful for the different place-based studies. The case studies showed that generalised models like the cascade can have an important ‘awareness-raising’ role. However, we found that using models of this kind it was more difficult for case studies to link their work to broader societal issues such as human well-being, sustainable ecosystem management, governance, and competitiveness, than to their own concerns. We therefore conclude that to be used effectively, conceptual models like the cascade may need to be supported by other materials that help users read it in different, outward looking ways. We also need to find mechanisms for capturing this experience so that it can be shared with others.

Quang, D. V., P. Schreinemachers and T. Berger (2014). "Ex-ante assessment of soil conservation methods in the uplands of Vietnam: An agent-based modeling approach." Agricultural Systems **123**: 108-119.

Agriculture in mountainous areas in Vietnam has much intensified since the introduction of market-based reforms in the mid 1980s. The adoption of hybrid maize varieties, mineral fertilizers and reduction in fallow periods has improved farm incomes, but has also led to a dramatic increase in soil erosion from sloping lands which has created a downward pressure on crop yields and has had adverse effects on downstream areas. This study explores the relationship between soil fertility, crop yields and the use of soil conservation methods by applying an agent-based modeling approach that combines whole-farm mathematical programming to simulate the decision-making of each individual farm household with a biophysical simulator of crop yields and soil fertility dynamics for each individual landscape unit. Simulation results suggest an average soil loss is 30 tons for maize fields and 27 tons for cassava fields per hectare per annum under present economic conditions, which is in the range of what other studies have measured, and a consequent decline in the average household incomes by 28.5% over a 25 years period. The introduction of three soil conservation methods in maize (vetiver grass strips, ruzi grass barriers and leucaena hedges) shows that these are not economical for farm households to adopt under present conditions, chiefly because of lower short-term maize yields. We explore the effect of giving farm households monetary incentives to adopt soil conservation and find that the payment needed for reducing 40 ± 2% of the estimated soil loss would be about 12–16 USD per ton of soil saved.

MP-MAS

Soil erosion

Soil conservation

Technology adoption

Integrated modeling

Farming systems research

Ramirez-Gomez, S. O. I., P. Verweij, L. Best, R. van Kanten, G. Rambaldi and R. Zagt (2017). "Participatory 3D modelling as a socially engaging and user-useful approach in ecosystem service assessments among marginalized communities." Applied Geography **83**: 63-77.

Rammer, W. and R. Seidl (2015). "Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes." Global Environmental Change **35**: 475-485.

Global change poses considerable challenges for ecosystems and their managers. To address these challenges it is increasingly clear that a coupled human and natural systems perspective is needed. While this science has advanced greatly in recent years, its mainstreaming into operational ecosystem management has proven to be difficult. One aspect complicating the application of a coupled human and natural systems approach has been the lack of tools that are simultaneously able to accommodate the complexities of ecological and social systems. However, neglecting their full interactions and feedbacks could lead to either an overestimation of the systems’ vulnerability to global change (e.g., where the social adaptive capacity is disregarded in assessments based solely on ecosystem models), or to the pretense of stability (e.g., where the dynamic responses of ecosystem processes to environmental changes are neglected in models of the social system). These issues are of particular importance in forest ecosystems, where human interventions affect ecosystem dynamics for decades to centuries. In order to improve the assessments of future forest trajectories, our objectives here were (i) to operationalize and describe the coupling of human and natural systems in the context of landscape-scale forest ecosystem management, and (ii) to demonstrate simulated interactions between the social and ecological spheres in the context of adaptation to a changing climate. We developed an agent-based model accounting for different spatial (stand and management unit) and temporal (operational and strategic) levels of forest management decision making and coupled it with the forest landscape simulator iLand. We show that the coupled human and natural systems model is autonomously able to reproduce meaningful trajectories of managed mountain forest landscape in Central Europe over the extended period of multiple centuries. Experimenting with different decision heuristics of managing agents suggests that both passive (reactive) and active (prospective) adaptive behavior might be necessary to successfully stabilize system trajectories under rapidly changing environmental conditions. Furthermore, investigating multi-agent landscapes we found that diversity in managerial responses to environmental changes increases the heterogeneity on the landscape, with positive effects on the temporal stability of ecosystem trajectories. We conclude that an integrated consideration of human and natural systems is important to realistically project trajectories of managed forests under global change, and highlight the potential of social–ecological feedbacks and heterogeneity in stabilizing the provisioning of ecosystem services in a changing environment.

Rasch, S., T. Heckelei and R. Johannes Oomen (2016). "Reorganizing resource use in a communal livestock production socio-ecological system in South Africa." Land Use Policy **52**: 221-231.

Livestock production on South Africa’s commons contributes significantly to the livelihoods of communal households, offering status, food, income and savings. Management innovations are generally top-down and informed by commercial practices such as rotational grazing in combination with conservative stocking. Implementations often ignore how the specific socio-ecological context affects outcomes and the impact on equity. Science now acknowledges that rangeland management must be context specific and that a universally agreed-upon recommendation for managing semi-arid rangelands does not exist. We present a socio-ecological simulation model derived from a case study in South Africa and use it to assess the socio-ecological effects of rotational vs. continuous grazing under conservative and opportunistic stocking rates. We find that continuous grazing under conservative stocking rates leads to the most favourable outcomes from the social and the ecological perspectives. However, the past legacy under apartheid and participants’ expectations renders its successful application unlikely because enforceability is not ensured.

Rasch, S., T. Heckelei, R. Oomen and C. Naumann (2016). "Cooperation and collapse in a communal livestock production SES model – A case from South Africa." Environmental Modelling & Software **75**: 402-413.

Institutional arrangements are considered necessary for successfully governing the commons. They are considered to be most effective if they are self-organized rather than imposed from outside. However, endogenous institutional arrangements, such as local norms, are specific to a particular socio-ecological system (SES). This paper presents a SES model of communal livestock producers in South Africa. Its bio-physical component accounts for the impact of biotic and abiotic factors on livestock population. The social agent-based component models individual and socially determined behaviour, the latter of which is a social norm specific to the case. Model results show that when cooperative agents obey and sanction the norm, there is less likelihood of SES collapse in terms of livestock population crashes. However, cooperation among agents only emerges in times of ecological crisis where social reorganization is fostered. The crisis creates an opportunity for initializing a self-enforcing process of mutual cooperation. Model specifications are based on survey data, and agents were parameterized according to individual household data. A sensitivity analysis shows that this empirical heterogeneity cannot be reduced without changing model outcomes.

Rasch, S., T. Heckelei, H. Storm, R. Oomen and C. Naumann (2017). "Multi-scale resilience of a communal rangeland system in South Africa." Ecological Economics **131**: 129-138.

Resilience has either been assessed on system or individual scale so far. Ignoring the other scale may potentially change the interpretation of resilience in socio-ecological systems (SES). Thus, this paper argues that the co-evolution of both resiliencies must be studied to capture multi-scale complexity. We attempt to close this gap by assessing resilience at both scales of a village community in Thaba Nchu, South Africa. Villagers use a commonly managed rangeland for beef cattle production. An agent based model of household interaction coupled with a biophysical model of the rangeland measures the resiliencies of the SES towards a shock, a stress and a policy intervention. Currently, the SES remains in a stable attractor in terms of SES resilience. Household resilience, however, degrades in a process of structural change. A drought scenario shows improved SES resilience but structural change at household level accelerated. An increase in the number absentee herders increases the likelihood for SES collapse by eroding social embededdness. Finally, an introduced basic income grant demonstrates that the SES is able to cope with an increased number of appropriators. However, interaction of the policy intervention with an exogenous stress translates into an increased probability of SES decoupling.

Reyers, B., J. L. Nel, P. J. O’Farrell, N. Sitas and D. C. Nel (2015). "Navigating complexity through knowledge coproduction: Mainstreaming ecosystem services into disaster risk reduction." Proceedings of the National Academy of Sciences **112**(24): 7362-7368.

Achieving the policy and practice shifts needed to secure ecosystem services is hampered by the inherent complexities of ecosystem services and their management. Methods for the participatory production and exchange of knowledge offer an avenue to navigate this complexity together with the beneficiaries and managers of ecosystem services. We develop and apply a knowledge coproduction approach based on social–ecological systems research and assess its utility in generating shared knowledge and action for ecosystem services. The approach was piloted in South Africa across four case studies aimed at reducing the risk of disasters associated with floods, wildfires, storm waves, and droughts. Different configurations of stakeholders (knowledge brokers, assessment teams, implementers, and bridging agents) were involved in collaboratively designing each study, generating and exchanging knowledge, and planning for implementation. The approach proved useful in the development of shared knowledge on the sizable contribution of ecosystem services to disaster risk reduction. This knowledge was used by stakeholders to design and implement several actions to enhance ecosystem services, including new investments in ecosystem restoration, institutional changes in the private and public sector, and innovative partnerships of science, practice, and policy. By bringing together multiple disciplines, sectors, and stakeholders to jointly produce the knowledge needed to understand and manage a complex system, knowledge coproduction approaches offer an effective avenue for the improved integration of ecosystem services into decision making.

Rounsevell, M. D. A., D. T. Robinson and D. Murray-Rust (2012). "From actors to agents in socio-ecological systems models." Philosophical Transactions of the Royal Society B: Biological Sciences **367**(1586): 259-269.

The ecosystem service concept has emphasized the role of people within socio-ecological systems (SESs). In this paper, we review and discuss alternative ways of representing people, their behaviour and decision-making processes in SES models using an agent-based modelling (ABM) approach. We also explore how ABM can be empirically grounded using information from social survey. The capacity for ABM to be generalized beyond case studies represents a crucial next step in modelling SESs, although this comes with considerable intellectual challenges. We propose the notion of human functional types, as an analogy of plant functional types, to support the expansion (scaling) of ABM to larger areas. The expansion of scope also implies the need to represent institutional agents in SES models in order to account for alternative governance structures and policy feedbacks. Further development in the coupling of human-environment systems would contribute considerably to better application and use of the ecosystem service concept.%U http://rstb.royalsocietypublishing.org/content/royptb/367/1586/259.full.pdf

Rova, S. and F. Pranovi (2017). "Analysis and management of multiple ecosystem services within a social-ecological context." Ecological Indicators **72**: 436-443.

The assessment of ecosystem services (ESS) requires approaches that are capable to deal with the complexity of social-ecological systems (SES). A new viewpoint is proposed, in which the social-ecological perspective of Ostrom’s SES framework is used to describe the flow of ESS, through the identification of the social and ecological elements involved. Two types of ESS flow emerge from this analysis, depending on the way in which the elements of ESS supply (resource system and resource units) and demand (actors) interact: (i) a “direct flow type” in which the resource units deliver the ESS through some specific ecological functions (e.g. wetlands providing carbon sequestration), and (ii) a “mediated flow type” in which the resource units become themselves the ESS when “used” by means of human activities (e.g. fish harvested through fishing activities). The identification of activities is crucial to understand the interactions between ESS, because of the feedbacks they produce on the ecosystem functioning and thus on the provision of the same or other ESS. In addition, these feedbacks can depend on temporal aspects of ESS provision. On these regards, a hypothesis is proposed according to which a time lag can exist between the ESS supply-side and flow in human-modified SES. Altogether, this social-ecological analysis of ESS can contribute to focus the management strategies on the control of impacting activities and on the maintenance of those processes which underpin ESS’ provision, thus contributing to the implementation of an ecosystem-based management of SES. These aspects are discussed in the light of the Venice lagoon example.

Sahrbacher, C., M. Brady, Y. Clough, C. Dong, U. Sahlin and M. Stjernmand (2014). Modelling spatial relationships between ecosystem services and agricultural production in an agent-based model. 7th Int. Congress on Env. Modelling and Software, San Diego, CA, USA, International Environmental Modelling and Software Society (iEMSs).

The collective impacts of farmers’ land management decisions on above ground ecosystem services (ES) and their implications for agriculture are poorly understood. Managing habitat to provide ES is costly but at the same time it can support higher yields through, e.g., pollination or natural pest control. Due to the mobility of ES-providers (bees, natural enemies) farmers providing habitat might also benefit their neighbours, creating interdependencies among their decisions. Interdependencies among farmers’ land-use decisions and the flow of ES in space can be considered by integrating agent-based modelling and evidence-based ES models. Such integration requires a trade-off between the land-use details required to capture relevant ecological dynamics of ES in a landscape and the simplified landscape modelling in agent-based models. This paper shows how details of land use can be increased in the agent-based model AgriPoliS that simulates agricultural structural change. Non-agricultural land in AgriPoliS is differentiated into different land uses, i.e. settlements and natural habitats. Furthermore, the size distribution of these landscape elements and their distribution in space are considered. The improvement of the landscape modelling is a prerequisite for detailed analysis of policies supporting biodiversity and their impact on agricultural production and farm income.

Schlüter, M., A. Baeza, G. Dressler, K. Frank, J. Groeneveld, W. Jager, M. A. Janssen, R. R. J. McAllister, B. Müller, K. Orach, N. Schwarz and N. Wijermans (2017). "A framework for mapping and comparing behavioural theories in models of social-ecological systems." Ecological Economics **131**: 21-35.

Formal models are commonly used in natural resource management (NRM) to study human-environment interactions and inform policy making. In the majority of applications, human behaviour is represented by the rational actor model despite growing empirical evidence of its shortcomings in NRM contexts. While the importance of accounting for the complexity of human behaviour is increasingly recognized, its integration into formal models remains a major challenge. The challenges are multiple: i) there exist many theories scattered across the social sciences, ii) most theories cover only a certain aspect of decision-making, iii) they vary in their degree of formalization, iv) causal mechanisms are often not specified. We provide a framework- MoHuB (Modelling Human Behavior) - to facilitate a broader inclusion of theories on human decision-making in formal NRM models. It serves as a tool and common language to describe, compare and communicate alternative theories. In doing so, we not only enhance understanding of commonalities and differences between theories, but take a first step towards tackling the challenges mentioned above. This approach may enable modellers to find and formalize relevant theories, and be more explicit and inclusive about theories of human decision making in the analysis of social-ecological systems.

Schreinemachers, P. and T. Berger (2011). "An agent-based simulation model of human–environment interactions in agricultural systems." Environmental Modelling & Software **26**(7): 845-859.

This paper describes an agent-based software package, called Mathematical Programming-based Multi Agent Systems (MP-MAS), which builds on a tradition of using constrained optimization to simulate farm decision-making in agricultural systems. The purpose of MP-MAS is to understand how agricultural technology, market dynamics, environmental change, and policy intervention affect a heterogeneous population of farm households and the agro-ecological resources these households command. The software is presented using the Overview, Design concepts, and Details (ODD) protocol. Modeling features are demonstrated with empirical applications to study sites in Chile, Germany, Ghana, Thailand, Uganda, and Vietnam. We compare MP-MAS with eight other simulators of human–environment interactions (ABSTRACT, CATCHSCAPE, ECECMOD, IMT, LUDAS, PALM, SAM, and SIM). The comparison shows that the uniqueness of MP-MAS lies in its combination of a microeconomic modeling approach and a choice of alternative biophysical modules that are either coded as part of the software or coupled with it using the Typed Data Transfer (TDT) library.

Schulze, J., B. Müller, J. Groeneveld and V. Grimm (2017). "Agent-Based Modelling of Social-Ecological Systems: Achievements, Challenges, and a Way Forward." Journal of Artificial Societies & Social Simulation **20**(2): 2-2.

Understanding social-ecological systems (SES) is crucial to supporting the sustainable management of resources. Agent-based modelling is a valuable tool to achieve this because it can represent the behaviour and interactions of organisms, human actors and institutions. Agent-based models (ABMs) have therefore already been widely used to study SES. However, ABMs of SES are by their very nature complex. They are therefore difficult to parameterize and analyse, which can limit their usefulness. It is time to critically reflect upon the current state-of-the-art to evaluate to what degree the potential of agent-based modelling for gaining general insights and supporting specific decision-making has already been utilized. We reviewed achievements and challenges by building upon developments in good modelling practice in the field of ecological modelling with its longer history. As a reference, we used the TRACE framework, which encompasses elements of model development, testing and analysis. We firstly reviewed achievements and challenges with regard to the elements of the TRACE framework addressed in reviews and method papers of social-ecological ABMs. Secondly, in a mini-review, we evaluated whether and to what degree the elements of the TRACE framework were addressed in publications on specific ABMs. We identified substantial gaps with regard to (1) communicating whether the models represented real systems well enough for their intended purpose and (2) analysing the models in a systematic and transparent way so that model output is not only observed but also understood. To fill these gaps, a joint effort of the modelling community is needed to foster the advancement and use of strategies such as participatory approaches, standard protocols for communication, sharing of source code, and tools and strategies for model design and analysis. Throughout our analyses, we provide specific recommendations and references for improving the state-of-the-art. We thereby hope to contribute to the establishment of a new advanced culture of agent-based modelling of SES that will allow us to better develop general theory and practical solutions. [ABSTRACT FROM AUTHOR]

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Scoones, I. (1998). Sustainable rural livelihoods: a framework for analysis. IDS Working Paper 72. Brighton, UK, University of Sussex.

Scoones, I. (2009). "Livelihoods perspectives and rural development." The Journal of Peasant Studies **36**(1): 171-196.

Livelihoods perspectives have been central to rural development thinking and practice in the past decade. But where do such perspectives come from, what are their conceptual roots, and what influences have shaped the way they have emerged? This paper offers an historical review of key moments in debates about rural livelihoods, identifying the tensions, ambiguities and challenges of such approaches. A number of core challenges are identified, centred on the need to inject a more thorough-going political analysis into the centre of livelihoods perspectives. This will enhance the capacity of livelihoods perspectives to address key lacunae in recent discussions, including questions of knowledge, politics, scale and dynamics.

Sen, A. (1997). "Editorial: Human capital and human capability." World Development **25**(12): 1959-1961.

Sinare, H., L. J. Gordon and E. Enfors Kautsky (2016). "Assessment of ecosystem services and benefits in village landscapes – A case study from Burkina Faso." Ecosystem Services **21**: 141-152.

Most methods to assess ecosystem services have been developed on large scales and depend on secondary data. Such data is scarce in rural areas with widespread poverty. Nevertheless, the population in these areas strongly depends on local ecosystem services for their livelihoods. These regions are in focus for substantial landscape investments that aim to alleviate poverty, but current methods fail to capture the vast range of ecosystem services supporting livelihoods, and can therefore not properly assess potential trade-offs and synergies among services that might arise from the interventions. We present a new method for classifying village landscapes into social-ecological patches (landscape units corresponding to local landscape perceptions), and for assessing provisioning ecosystem services and benefits to livelihoods from these patches. We apply the method, which include a range of participatory activities and satellite image analysis, in six villages across two regions in Burkina Faso. The results show significant and diverse contributions to livelihoods from six out of seven social-ecological patches. The results also show how provisioning ecosystem services, primarily used for subsistence, become more important sources of income during years when crops fail. The method is useful in many data poor regions, and the patch-approach allows for extrapolation across larger spatial scales with similar social-ecological systems.

Smajgl, A. and J. Ward (2013). "A framework to bridge science and policy in complex decision making arenas." Futures **52**(Supplement C): 52-58.

We argue that science concerned with natural resource policy analysis is entering a new phase. In response to policy demands for triple-bottom-line assessments, developing transdisciplinary endeavours has been a primary focus, catalysing methodological innovations. However, the period of innovation has increased the divergence between a science domain characterised by increasing complexity of communicated analytical outputs and a policy domain that generally remains impelled towards single metric outcomes. We argue that this new phase will see the focus shift from method innovation towards the design of research processes to correct the discrepancy. This paper describes the Challenge-and-Reconstruct Learning framework (ChaRL) for designing sustainability-focused research processes to better align science contributions and policy aspirations in complex decision making arenas. This paper provides evidence for how the ChaRL framework can (1) establish and maintain an effective science–policy interface despite high levels of complexity and high levels of contested values and (2) challenge and reconstruct existing knowledge, providing a robust foundation to evidence-based decision making. Critical for these achievements is that the design of the engagement process starts with the cognitive elements critical to the decision making processes, that is individuals’ causal beliefs and values.

Spangenberg, J. (2018). "Behind the Scenarios: World View, Ideologies, Philosophies. An Analysis of Hidden Determinants and Acceptance Obstacles Illustrated by the ALARM Scenarios." Sustainability **10**(7): 2556.

Spangenberg, J. H. (2016). "Blind Spots of Interdisciplinary Collaboration Monetising Biodiversity: Before Calculating the Value of Nature, Reflect on the Nature of Value." Cadmus **3**(1): 115.

Spangenberg, J. H., A. L. Beaurepaire, E. Bergmeier, B. Burkhard, H. Van Chien, L. Q. Cuong, C. Görg, V. Grescho, L. H. Hai, K. L. Heong, F. G. Horgan, S. Hotes, A. Klotzbücher, T. Klotzbücher, I. Kühn, F. Langerwisch, G. Marion, R. F. A. Moritz, Q. A. Nguyen, J. Ott, C. Sann, C. Sattler, M. Schädler, A. Schmidt, V. Tekken, T. D. Thanh, K. Thonicke, M. Türke, T. Václavík, D. Vetterlein, C. Westphal, M. Wiemers and J. Settele (2018). "The LEGATO cross-disciplinary integrated ecosystem service research framework: an example of integrating research results from the analysis of global change impacts and the social, cultural and economic system dynamics of irrigated rice production." Paddy and Water Environment **16**(2): 287-319.

In a cross-disciplinary project (LEGATO) combining inter- and transdisciplinary methods, we quantify the dependency of rice-dominated socio-ecological systems on ecosystem functions (ESF) and the ecosystem services (ESS) the integrated system provides. In the collaboration of a large team including geo- and bioscientists, economists, political and cultural scientists, the mutual influences of the biological, climate and soil conditions of the agricultural area and its surrounding natural landscape have been analysed. One focus was on sociocultural and economic backgrounds, another on local as well as regional land use intensity and biodiversity, and the potential impacts of future climate and land use change. LEGATO analysed characteristic elements of three service strands defined by the Millennium Ecosystem Assessment (MA): (a) provisioning services: nutrient cycling and crop production; (b) regulating services: biocontrol and pollination; and (c) cultural services: cultural identity and aesthetics. However, in line with much of the current ESS literature, what the MA called supporting services is treated as ESF within LEGATO. As a core output, LEGATO developed generally applicable principles of ecological engineering (EE), suitable for application in the context of future climate and land use change. EE is an emerging discipline, concerned with the design, monitoring and construction of ecosystems and aims at developing strategies to optimise ecosystem services through exploiting natural regulation mechanisms instead of suppressing them. Along these lines LEGATO also aims to create the knowledge base for decision-making for sustainable land management and livelihoods, including the provision of the corresponding governance and management strategies, technologies and system solutions.

Spangenberg, J. H., C. Görg, D. T. Truong, V. Tekken, J. V. Bustamante and J. Settele (2014). "Provision of ecosystem services is determined by human agency, not ecosystem functions. Four case studies." International Journal of Biodiversity Science, Ecosystem Services & Management **10**(1): 40-53.

Ecosystem services (ESS) are frequently described as nature?s free gift to humankind. However, the first step of ESS and benefit generation is recognising the usability of structures, processes and outputs of ecosystems. This use-value attribution transforms the ecosystem functions (ESF) into ecosystem service potentials (ESP). By investing physical resources, energy and labour, and frequently money as a means to provide them, agents mobilise (part of) the potentials. Cultural, economic and legal constraints limit the mobilisation. The resulting ESS are appropriated to be directly consumed, exploited to provide other goods and services, or marketed, resulting in monetary income. Changing use-value attribution leads to change service potentials, to different mobilisation and appropriation patterns, and different benefits. Human agency, not ESF determine the services provided. This is illustrated by comparing traditional and current services generated from the same ecosystem in four countries undergoing socio-economic transitions: Kenya, Mongolia, the Philippines and Vietnam. All four cases show that changing habits, preferences and modes of regulation lead to specific services provided. Institutions such as tradition, belief systems, markets or state planning are the key to understand which ESS are generated from any ESF. Value attribution, mobilisation and appropriation are key processes.

Sun, Z., I. Lorscheid, J. D. Millington, S. Lauf, N. R. Magliocca, J. Groeneveld, S. Balbi, H. Nolzen, B. Müller, J. Schulze and C. M. Buchmann (2016). "Simple or complicated agent-based models? A complicated issue." Environmental Modelling & Software **86**: 56-67.

Agent-based models (ABMs) are increasingly recognized as valuable tools in modelling human-environmental systems, but challenges and critics remain. One pressing challenge in the era of “Big Data” and given the flexibility of representation afforded by ABMs, is identifying the appropriate level of complicatedness in model structure for representing and investigating complex real-world systems. In this paper, we differentiate the concepts of complexity (model behaviour) and complicatedness (model structure), and illustrate the non-linear relationship between them. We then systematically evaluate the trade-offs between simple (often theoretical) models and complicated (often empirically-grounded) models. We propose using pattern-oriented modelling, stepwise approaches, and modular design to guide modellers in reaching an appropriate level of model complicatedness. While ABMs should be constructed as simple as possible but as complicated as necessary to address the predefined research questions, we also warn modellers of the pitfalls and risks of building “mid-level” models mixing stylized and empirical components.

Sun, Z. and D. Müller (2013). "A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models." Environmental Modelling & Software **45**: 15-28.

We present an integrated modeling framework for simulating land-use decision making under the influence of payments for ecosystem services. The model combines agent-based modeling (ABM) with Bayesian belief networks (BBNs) and opinion dynamics models (ODM). The model endows agents with the ability to make land-use decisions at the household and plot levels. The decision-making process is captured with the BBNs that were constructed and calibrated with both qualitative and quantitative information, i.e., knowledge gained from group discussions with stakeholders and empirical survey data. To represent interpersonal interactions within social networks, the decision process is further modulated by the opinion dynamics model. The goals of the model are to improve the ability of ABM to emulate land-use decision making and thus provide a better understanding of the potential impacts of payments for ecosystem services on land use and household livelihoods. Our approach provides three important innovations. First, decision making is represented in a causal directed graph. Second, the model provides a natural framework for combining knowledge from experts and stakeholders with quantitative data. Third, the modular architecture and the software implementation can be customized with modest efforts. The model is therefore a flexible, general platform that can be tailored to other studies by mounting the appropriate case-specific “brain” into the agents. The model was calibrated for the Sloping Land Conversion Program (SLCP) in Yunnan, China using data from participatory mapping, focus group interviews, and a survey of 509 farm households in 17 villages.

Tarrasón, D., F. Ravera, M. S. Reed, A. J. Dougill and L. Gonzalez (2016). "Land degradation assessment through an ecosystem services lens: Integrating knowledge and methods in pastoral semi-arid systems." Journal of Arid Environments **124**: 205-213.

This paper develops and applies an integrated and participatory methodological framework to assess land degradation in pastoral systems through an ecosystem services (ES) lens in a semi-arid region of northern Nicaragua. We initially integrated local and scientific knowledge to assess ecological changes and understand the links with ecosystem services supplied by the local grazing system. Hence, we discuss land degradation features and test a state-and-transition ecological model, that is, we developed jointly with local farmers the hypotheses to understand transitions between ecological states and these hypotheses were then evaluated through an inventory of vegetation and an assessment of soil properties and seed bank composition. The assessment reveals that shifts in ecological state do not cause permanent soil properties changes, but that at a landscape scale they can limit production, affecting local livelihoods. The framework proposed provided local farmers with relevant information and facilitated communication with researchers, enabling them to use the co-constructed knowledge to implement adaptive management strategies to improve local productive systems.

Tesfatsion, L., C. R. Rehmann, D. S. Cardoso, Y. Jie and W. J. Gutowski (2017). "An agent-based platform for the study of watersheds as coupled natural and human systems." Environmental Modelling & Software **89**: 40-60.

This study describes the architecture and capabilities of an open source agent-based Java platform that permits the systematic study of interactions among hydrology, climate, and strategic human decision-making in a watershed over time. To demonstrate the platform's use and capabilities, an application is presented in accordance with ODD protocol requirements that captures, in simplified form, the structural attributes of the Squaw Creek watershed in central Iowa. Illustrative findings are reported for the sensitivity of farmer and city social welfare outcomes to changes in three key treatment factors: farmer land-allocation decision method, farmer targeted savings, and levee quality effectiveness for the mitigation of city flood damage.

Turner Ii, B. L., K. J. Esler, P. Bridgewater, J. Tewksbury, N. Sitas, B. Abrahams, F. S. Chapin, R. R. Chowdhury, P. Christie, S. Diaz, P. Firth, C. N. Knapp, J. Kramer, R. Leemans, M. Palmer, D. Pietri, J. Pittman, J. Sarukhán, R. Shackleton, R. Seidler, B. van Wilgen and H. Mooney (2016). "Socio-Environmental Systems (SES) Research: what have we learned and how can we use this information in future research programs." Current Opinion in Environmental Sustainability **19**: 160-168.

The call for integrated social–environmental science, complete with outreach to applications and solutions, is escalating worldwide. Drawing on several decades of experience, researchers engaged in such science, completed an assessment of the design and management attributes and impact pathways that lead to successful projects and programs and to understand key impediments to success. These characteristics are delineated and discussed using examples from individual projects and programs. From this, three principal lessons leading to successful efforts emerge that address co-design, adaptive or flexible management, and diversity of knowledge. In addition, five challenges for this science are identified: accounting for change, addressing sponsorship and timelines, appreciating different knowledge systems, adaptively communicating, and improving linkages to policy.

Valdivia, C. (2004). "Andean Livelihood Strategies and the Livestock Portfolio." Culture & Agriculture **26**(1‐2): 69-79.

van Oudenhoven, A. P. E., K. Petz, R. Alkemade, L. Hein and R. S. de Groot (2012). "Framework for systematic indicator selection to assess effects of land management on ecosystem services." Ecological Indicators **21**: 110-122.

Land management is an important factor that affects ecosystem services provision. However, interactions between land management, ecological processes and ecosystem service provision are still not fully understood. Indicators can help to better understand these interactions and provide information for policy-makers to prioritise land management interventions. In this paper, we develop a framework for the systematic selection of indicators, to assess the link between land management and ecosystem services provision in a spatially explicit manner. Our framework distinguishes between ecosystem properties, ecosystem functions, and ecosystem services. We tested the framework in a case study in The Netherlands. For the case study, we identified 12 property indicators, 9 function indicators and 9 service indicators. The indicators were used to examine the effect of land management on food provision, air quality regulation and recreation opportunities. Land management was found to not only affect ecosystem properties, but also ecosystem functions and services directly. Several criteria were used to evaluate the usefulness of the selected indicators, including scalability, sensitivity to land management change, spatial explicitness, and portability. The results show that the proposed framework can be used to determine quantitative links between indicators, so that land management effects on ecosystem services provision can be modelled in a spatially explicit manner.

van Wijk, M. T., M. C. Rufino, D. Enahoro, D. Parsons, S. Silvestri, R. O. Valdivia and M. Herrero (2012). "A review on farm household modelling with a focus on climate change adaptation and mitigation."

Villamagna, A. and C. Giesecke (2014). "Adapting Human Well-being Frameworks for Ecosystem Service Assessments across Diverse Landscapes." Ecology and Society **19**(1): 18.

There is broad support for the notion that ecosystem services influence human well-being (HWB), however, the means to measure such an effect are elusive. Measures of HWB are commonly used within the fields of psychology, economics, and international development, but thus far have not been integrated fully into ecosystem service assessments. We examine the multidimensional nature of HWB and discuss the need for a robust framework that captures its complex relationship with ecosystem services. We review several well-known HWB indices and describe the adaptation of two frameworks-the Economist Intelligence Unit's Quality of Life Index and the Sustainable Livelihoods Framework-to evaluate county-level HWB within the Albemarle-Pamlico Basin (Virginia and North Carolina, USA) using a stakeholder-engaged approach. We present maps of HWB that illustrate the results of both frameworks, discuss the feedback from stakeholders that guided indicator and data selection, and examine the observed differences in HWB throughout the basin. We conclude with suggestions for enhancing the role of ecosystem services in HWB indices.

Villamor, G. B., Q. B. Le, U. Djanibekov, M. van Noordwijk and P. L. G. Vlek (2014). "Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra." Environmental Modelling & Software **61**: 151-165.

Rubber agroforests in the mostly deforested lowlands of Sumatra, Indonesia are threatened by conversion into monoculture rubber or oil palm plantations. We applied an agent-based model to explore the potential effectiveness of a payment for ecosystem services (PES) design through a biodiversity rich rubber eco-certification scheme. We integrated conditionality, where compliance with biodiversity performance indicators is prerequisite for awarding incentives. We compared a PES policy scenario to ‘business-as-usual’ and ‘subsidized land use change’ scenarios to explore potential trade-offs between ecosystem services delivery and rural income. Results indicated that a rubber agroforest eco-certification scheme could reduce carbon emissions and species loss better than alternative scenarios. However, the suggested premiums were too low to compete with income from other land uses. Nevertheless, integrating our understanding of household agent behavior through a spatially explicit and agent-specific assessment of the trade-offs can help refine the design of conservation initiatives such as PES.

Villamor, G. B. and M. van Noordwijk (2016). "Gender specific land-use decisions and implications for ecosystem services in semi-matrilineal Sumatra." Global Environmental Change **39**: 69-80.

Gender specificity with respect to land-use options and responsiveness to agents that offer related investment opportunities is poorly understood. We combined agent-based modeling and experimental role playing games to compare land-use preferences and decisions between men and women in a landscape dominated by rubber agroforests in Sumatra, Indonesia. Ecosystem service delivery can be influenced by gender specific land-use preferences, especially in areas under conservation agreements. The research methods were designed to examine gender aspects of three ‘bounds’ of human nature (bounded rationality, bounded willpower and bounded self-interests) in relation to land-use decisions. Rice fields (mostly owned and inherited by females) provide part of local staple food needs in the study area, whereas rubber agroforests provide income in addition to resources for local use and rubber and oil palm monocultures are fully market oriented. In both the model and game exercises, men preferred the status quo rice production in combination with agroforest land uses, but women preferred the conversion of agroforest to more financially profitable monoculture systems, with increased carbon emissions as side effect. Although both genders exhibited similar preferences for ecosystem service provision, regulatory ecosystem services (i.e., climate and water regulation) were reduced by women’s landuse choices. Thus, ecosystem service tradeoffs are potentially greater in women-dominated landscapes under these circumstances. Furthermore, gender-specific limitations and socio-cultural contexts (i.e., matrilineal societies) may influence the flow of ecosystem services as well as landscape patterns.

Vinatier, F., P. Lagacherie, M. Voltz, S. Petit, C. Lavigne, Y. Brunet and F. Lescourret (2016). "An Unified Framework to Integrate Biotic, Abiotic Processes and Human Activities in Spatially Explicit Models of Agricultural Landscapes." Frontiers in Environmental Science **4**(6).

Recent concern over possible ways to sustain ecosystem services has triggered important research worldwide on ecosystem processes at the landscape scale. Understanding this complexity of landscape functioning calls for coupled and spatially-explicit modelling approaches. However, disciplinary boundaries have limited the number of multi-process studies at the landscape scale, and current progress in coupling processes at this scale often reveals strong imbalance between biotic and abiotic processes, depending on the core discipline of the modellers. We propose a spatially-explicit, unified conceptual framework that allows researchers from different fields to develop a shared view of agricultural landscapes. In particular,we distinguish landscape elements that are mobile in space and represent biotic or abiotic objects (for example water, fauna or flora populations), and elements that are immobile and represent fixed landscape elements with a given geometry (for example ditch section or plot). The shared representation of these elements allows setting common objects and spatio-temporal process boundaries that may otherwise differ between disciplines. We present guidelines and an assessment of the applicability of this framework to a virtual landscape system with realistic properties. This framework allows the complex system to be represented with a limited set of concepts but leaves the possibility to include current modelling strategies specific to biotic or abiotic disciplines. Future operational challenges include model design, space and time discretization, and the availability of both landscape modelling platforms and data.

Voinov, A. and H. H. Shugart (2013). "‘Integronsters’, integral and integrated modeling." Environmental Modelling & Software **39**: 149-158.

In many cases model integration treats models as software components only, ignoring the fluid relationship between models and reality, the evolving nature of models and their constant modification and recalibration. As a result, with integrated models we find increased complexity, where changes that used to impact only relatively contained models of subsystems, now propagate throughout the whole integrated system. This makes it harder to keep the overall complexity under control and, in a way, defeats the purpose of modularity, when efficiency is supposed to be gained from independent development of modules. Treating models only as software in solving the integration challenge may give birth to ‘integronsters’ – constructs that are perfectly valid as software products but ugly or even useless as models. We argue that one possible remedy is to learn to use data sets as modules and integrate them into the models. Then the data that are available for module calibration can serve as an intermediate linkage tool, sitting between modules and providing a module-independent baseline dynamics, which is then incremented when scenarios are to be run. In this case it is not the model output that is directed into the next model input, but model output is presented as a variation around the baseline trajectory, and it is this variation that is then fed into the next module down the chain. However still with growing overall complexity, calibration can become an important limiting factor, giving more promise to the integral approach, when the system is modeled and simplified as a whole.

Walsh, S. J., J. P. Messina, C. F. Mena, G. P. Malanson and P. H. Page (2008). "Complexity theory, spatial simulation models, and land use dynamics in the Northern Ecuadorian Amazon." Geoforum **39**(2): 867-878.

Our research questions and analytical approaches are used to examine coupled human–natural systems in the Northern Ecuadorian Amazon. They are based on complexity theory and extend from our earlier work in Cellular Automata (CA) in which land use/land cover (LULC) change patterns were spatially simulated to examine deforestation and agricultural extensification on household farms. The basic intent is to understand linkages between people and the environment by explicitly considering pattern–process relationships and the nature of feedback mechanisms among social, biophysical, and geographical factors that influence LULC dynamics within the study area. In this research, we describe how our CA modeling approach emphasizes the human dimensions of LULC change by including socio-economic and demographic characteristics at the household-level along with biophysical data that describe the resource endowments of farms, geographic accessibility of farms to roads and communities, and the evolving nature of human–environment interactions over time and space in response to exogenous and endogenous factors. A LULC change scenario is examined by comparing model outcomes generated for a base CA model and an alternative CA model to explore the effects of increases in household income on land use change patterns at the farm level, achieved as a consequence of improved geographic accessibility to roads and communities and increased off-farm employment as a household livelihood strategy. Growth or transitions rules in our CA model, as well as neighborhood associations are sensitive to socio-economic and demographic factors of households, resource endowments of farms, geographic accessibility, and the uncertainty associated with peasant farming in a frontier setting. Model outcomes indicate that increases in household income are associated with more land in pasture and more land being cultivated for crops as a result of greater access to agricultural markets. In addition, more land in secondary forest succession occurs as a consequence of greater access to roads and communities, thereby, affording a better opportunity for off-farm employment and greater levels of household income.

Wieland, R., S. Ravensbergen, E. J. Gregr, T. Satterfield and K. M. A. Chan (2016). "Debunking trickle-down ecosystem services: The fallacy of omnipotent, homogeneous beneficiaries." Ecological Economics **121**: 175-180.

Ecosystem services research broadly assumes that an increased supply of nature's goods and services will yield increased benefits. We challenge this ‘trickle-down’ assumption by explicitly investigating the factors that might impede ecosystem services yielding benefits to different stakeholder groups, based on a targeted literature review of First Nations' access to shellfish on Canada's Pacific Coast. Our review revealed four sets of barriers to realizing benefits from ecosystem services despite their abundance within many First Nation territories. The barriers highlight problems of access, particularly as driven by geographic location, technical capacity, markets and user conflicts, and management (of harvest and access), all of which limit First Nations' procuring of resources linked to key services. Our findings demonstrate that simply increasing ecosystem service supply does not necessarily increase benefits for individuals or groups. Realizing the promise that ecosystem services research will enhance human well-being through improved management depends on the explicit consideration of how access mediates the distribution of benefits.

Wossen, T. and T. Berger (2015). "Climate variability, food security and poverty: Agent-based assessment of policy options for farm households in Northern Ghana." Environmental Science & Policy **47**: 95-107.

According to the majority of regional climate projections, Sub-Saharan Africa (SSA) will likely become warmer in the next decades and rainfall patterns will substantially shift. Understanding the effect of climate variability on food security and poverty and identifying effective adaptation measures in the context of subsistence agriculture is imperative to ensure food security now and in the future. This article presents a micro-level simulation study that was undertaken for Northern Ghana, building on the approach and data developed within a research project of the CGIAR Challenge Programme on Water and Food. The study applied agent-based modelling to analyse how adaptation affects the distribution of household food security and poverty under current climate and price variability. Specifically, we examined the effectiveness of policy interventions related to the promotion of agricultural credit and off-farm employment opportunities. Our simulation experiments suggest that both climate and price variability have a pronounced negative effect on household welfare. Moreover, we found substantial difference in the poverty and food security status of households due to climate and price variability. Provision of agricultural credit and access to off-farm employment are found to be highly effective policy entry points that deserve more empirical research.

Wossen, T., T. Berger, M. G. Haile and C. Troost (2017). "Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa." Agricultural Systems.

This paper provides an ex-ante assessment of the impacts of climate and price variability on household income and food security in Ethiopia and Ghana. The study applies an agent-based modelling approach to highlight the role of coping and adaptation strategies under climate and price variability. Our simulation results show that climate and price variability adversely affects income and food security of households in both countries. Self-coping mechanisms are found to be important but insufficient to mitigate the adverse effects of variability, implying the need for policy interventions. Adaptation strategies composed of a portfolio of actions such as the provision of production credit and access to improved seeds are found to be effective in reducing the impacts of climate and price variability in Ethiopia. Similarly, policy interventions aimed at improving the provision of short-term production credit along with the existing irrigation facilities are important in Ghana. Finally, this study highlights the importance of capturing the distributional aspects of adaptation options by highlighting heterogeneous effects of variability and adaptation options.

Zvoleff, A. and L. An (2014). "Analyzing Human–Landscape Interactions: Tools That Integrate." Environmental Management **53**(1): 94-111.

Humans have transformed much of Earth’s land surface, giving rise to loss of biodiversity, climate change, and a host of other environmental issues that are affecting human and biophysical systems in unexpected ways. To confront these problems, environmental managers must consider human and landscape systems in integrated ways. This means making use of data obtained from a broad range of methods (e.g., sensors, surveys), while taking into account new findings from the social and biophysical science literatures. New integrative methods (including data fusion, simulation modeling, and participatory approaches) have emerged in recent years to address these challenges, and to allow analysts to provide information that links qualitative and quantitative elements for policymakers. This paper brings attention to these emergent tools while providing an overview of the tools currently in use for analysis of human–landscape interactions. Analysts are now faced with a staggering array of approaches in the human–landscape literature—in an attempt to bring increased clarity to the field, we identify the relative strengths of each tool, and provide guidance to analysts on the areas to which each tool is best applied. We discuss four broad categories of tools: statistical methods (including survival analysis, multi-level modeling, and Bayesian approaches), GIS and spatial analysis methods, simulation approaches (including cellular automata, agent-based modeling, and participatory modeling), and mixed-method techniques (such as alternative futures modeling and integrated assessment). For each tool, we offer an example from the literature of its application in human–landscape research. Among these tools, participatory approaches are gaining prominence for analysts to make the broadest possible array of information available to researchers, environmental managers, and policymakers. Further development of new approaches of data fusion and integration across sites or disciplines pose an important challenge for future work in integrating human and landscape components.