Appendix for „The potential of models and modelling for social-ecological systems research – the reference frame MODSES"

Section 1: Selection of papers for review of resilience models (from 1998-2011)

We used the "Web of Science" database to identify relevant papers for our review. We searched for process-based modeling studies that dealt with resource management issues of social-ecological systems and were interested in resilience questions. We are aware that modeling studies that do not explicitly mention the term "resilience" but look at for instance "stability", "persistence" etc. may also contribute to resilience research. However in order to have a manageable number of papers we restricted the search to the term "resilience".

The exact query used was: **"TS=(resilience AND model AND ecol* AND (management OR resource OR governance))".** The search was carried out in April 2009 and repeated for papers from 2009 to 2011 in April 2012. 289 papers were detected by the search algorithm.

After reading the abstracts/the whole papers we eliminated those studies that did not fulfilled our criteria. For instance we did not want to investigate pure conceptual models which present only a system description or model framework without any model solution. Since we were interested in dynamic process-based models we excluded furthermore pure statistical models. Some of the studies presented a purely ecological model without any management or use - a further criterion for exclusion. Finally only 52 papers out of the 289 papers were left over for review (see below for a list of the papers). The years in which articles were published are depicted in Figure A1.

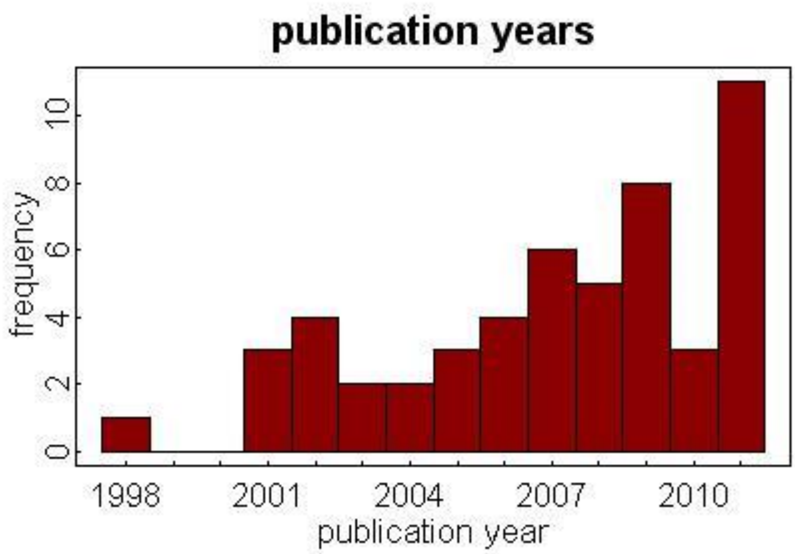

Figure A1: Years of publication

Papers included in review (from 1998-2011)

Albers, H. J.; Goldbach, M. J. & Kaffine, D. T. (2006), 'Implications of agricultural policy for species invasion in shifting cultivation systems', *ENVIRONMENT AND DEVELOPMENT ECONOMICS* **11**(4), 429-452.

Anderies, J.; Janssen, M. & Walker, B. (2002), 'Grazing management, resilience, and the dynamics of a fire-driven rangeland system', *ECOSYSTEMS* **5**(1), 23-44.

Anderies, J. M.; Ryan, P. & Walker, B. H. (2006), 'Loss of resilience, crisis, and institutional change: Lessons from an intensive agricultural system in southeastern Australia', *ECOSYSTEMS* **9**(6), 865-878.

Anderies, John M., and Michelle Hegmon. 2011. “Robustness and Resilience Across Scales: Migration and Resource Degradation in the Prehistoric US Southwest.” Ecology and Society 16 (2).

Baskett, Marissa L., Roger M. Nisbet, Carrie V. Kappel, Peter J. Mumby, and Steven D. Gaines. 2010. “Conservation Management Approaches to Protecting the Capacity for Corals to Respond to Climate Change: a Theoretical Comparison.” Global Change Biology 16 (4): 1229–1246.

Batabyal, A. (2002), 'Human actions, the survival of keystone species, and the resilience of ecological-economic systems', *RESOURCES POLICY* **28**(3-4), 153-157.

Batabyal, A. (2001), 'A theoretical inquiry into aspects of the structure and the management of ecological-economic systems', *STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT* **15**(2), 173-184.

Baumgaertner, Stefan, Sandra Derissen, Martin F. Quaas, and Sebastian Strunz. 2011. “Consumer Preferences Determine Resilience of Ecological-Economic Systems.” Ecology and Society 16 (4).

Blackwood, Julie C., and Alan Hastings. 2011. “The Effect of Time Delays on Caribbean Coral-algal Interactions.” Journal of Theoretical Biology 273 (1) :37–43.

Bodin, O. & Norberg, J. (2005), 'Information network topologies for enhanced local adaptive management', *ENVIRONMENTAL MANAGEMENT* **35**(2), 175-193.

Bolte, J. P.; Hulse, D. W.; Gregory, S. V. & Smith, C. (2007), 'Modeling biocomplexity - actors, landscapes and alternative futures', *ENVIRONMENTAL MODELLING & SOFTWARE* **22**(5 Sp. Iss. SI), 570-579.

Bueno, Newton, and Xavier Basurto. 2009. “Resilience and Collapse of Artisanal Fisheries: a System Dynamics Analysis of a Shellfish Fishery in the Gulf of California, Mexico.” Sustainability Science 4 (2): 139–149. doi:10.1007/s11625-009-0087-z.

Carpenter, S. & Brock, W. (2004), 'Spatial complexity, resilience, and policy diversity: Fishing on lake-rich landscapes', *ECOLOGY AND SOCIETY* **9**(1).

Carpenter, S. R. & Brock, W. A. (2008), 'Adaptive Capacity and Traps', *ECOLOGY AND SOCIETY* **13**(2).

Chapin, F.; Rupp, T.; Starfield, A.; DeWilde, L.; Zavaleta, E.; Fresco, N.; Henkelman, J. & McGuire, A. (2003), 'Planning for resilience: modeling change in human-fire interactions in the Alaskan boreal forest', *FRONTIERS IN ECOLOGY AND THE ENVIRONMENT* **1**(5), 255-261.

Chisholm, R. A. & Filotas, E. (2009), 'Critical slowing down as an indicator of transitions in two-species models', *Journal Of Theoretical Biology* **257**(1), 142--149.

Cordonnier, T.; Courbaud, B.; Berger, F. & Franc, A. (2008), 'Permanence of resilience and protection efficiency in mountain Norway spruce forest stands: A simulation study', *FOREST ECOLOGY AND MANAGEMENT* **256**(3), 347-354.

Dakos, Vasilis, Sonia Kefi, Max Rietkerk, Egbert H. van Nes, and Marten Scheffer. 2011. “Slowing Down in Spatially Patterned Ecosystems at the Brink of Collapse.” American Naturalist 177 (6): E153–E166. doi:10.1086/659945.

D'Alessandro, S. (2007), 'Non-linear dynamics of population and natural resources: The emergence of different patterns of development', *ECOLOGICAL ECONOMICS* **62**(3-4), 473-481.

Derissen, Sandra, Martin F. Quaas, and Stefan Baumgaertner. 2011. “The Relationship Between Resilience and Sustainability of Ecological-economic Systems.” Ecological Economics 70 (6) (April 15): 1121–1128. doi:10.1016/j.ecolecon.2011.01.003.

Dougill, Andrew J., Evan D. G. Fraser, and Mark S. Reed. 2010. “Anticipating Vulnerability to Climate Change in Dryland Pastoral Systems: Using Dynamic Systems Models for the Kalahari.” Ecology and Society 15 (2).

Figueiredo, Joana, and Henrique M. Pereira. 2011. “Regime Shifts in a Socio-ecological Model of Farmland Abandonment.” Landscape Ecology 26 (5: 737–749. doi:10.1007/s10980-011-9605-3.

Fletcher, C. S. & Hilbert, D. W. (2007), 'Resilience in landscape exploitation systems', *ECOLOGICAL MODELLING* **201**(3-4), 440-452.

Forbis, T. A.; Provencher, L.; Frid, L. & Medlyn, G. (2006), 'Great Basin Land Management planning using ecological modeling', *ENVIRONMENTAL MANAGEMENT* **38**(1), 62-83.

Gobattoni, Federica, Raffaele Pelorosso, Giuliana Lauro, Antonio Leone, and Roberto Monaco. 2011. “A Procedure for Mathematical Analysis of Landscape Evolution and Equilibrium Scenarios Assessment.” Landscape and Urban Planning 103 (3-4): 289–302. doi:10.1016/j.landurbplan.2011.08.011.

Grafton, R.; Kompas, T. & Lindenmayer, D. (2005), 'Marine reserves with ecological uncertainty', *BULLETIN OF MATHEMATICAL BIOLOGY* **67**(5), 957-971.

Grune, L.; Kato, M. & Semmler, W. (2005), 'Solving ecological management problems using dynamic programming', *JOURNAL OF ECONOMIC BEHAVIOR & ORGANIZATION* **57**(4), 448-473.

Guttal, V. & Jayaprakash, C. (2007), 'Impact of noise on bistable ecological systems', *ECOLOGICAL MODELLING* **201**(3-4), 420-428.

Guttal, Vishwesha, and C. Jayaprakash. 2008. “Spatial Variance and Spatial Skewness: Leading Indicators of Regime Shifts in Spatial Ecological Systems.” Theoretical Ecology 2 (1) (December 2): 3–12. doi:10.1007/s12080-008-0033-1.

Gutierrez, A. P, G. Gilioli, and J. Baumgärtner. 2009. “Ecosocial Consequences and Policy Implications of Disease Management in East African Agropastoral Systems.” Proceedings of the National Academy of Sciences 106 (31): 13136–13141.

Horan, Richard D., Eli P. Fenichel, Kevin L. S. Drury, and David M. Lodge. 2011. “Managing Ecological Thresholds in Coupled Environmental-human Systems.” Proceedings of the National Academy of Sciences of the United States of America 108 (18: 7333–7338. doi:10.1073/pnas.1005431108.

Leroux, A. D. & Creedy, J. (2007), 'Optimal land conversion and growth with uncertain biodiversity costs', *ECOLOGICAL ECONOMICS* **61**(2-3), 542-549.

Leslie, Heather M., Maja Schlüter, Richard Cudney-Bueno, and Simon A. Levin. 2009. “Modeling Responses of Coupled Social–ecological Systems of the Gulf of California to Anthropogenic and Natural Perturbations.” Ecological Research 24 (3) (April 24): 505–519. doi:10.1007/s11284-009-0603-8.

Li, Hongjun, Zhijun Liu, Li Zheng, and Yuping Lei. 2011. “Resilience Analysis for Agricultural Systems of North China Plain Based on a Dynamic System Model.” Scientia Agricola 68 (1): 8–17.

Loudermilk, E. L., W. P. Cropper, Jr., R. J. Mitchell, and H. Lee. 2011. “Longleaf Pine (Pinus Palustris) and Hardwood Dynamics in a Fire-maintained Ecosystem: A Simulation Approach.” Ecological Modelling 222 (15): 2733–2750. doi:10.1016/j.ecolmodel.2011.05.004.

Ludwig, D.; Carpenter, S. & Brock, W. (2003), 'Optimal phosphorus loading for a potentially eutrophic lake', *ECOLOGICAL APPLICATIONS* **13**(4), 1135-1152.

Ludwig, J.; Coughenour, M.; Liedloff, A. & Dyer, R. (2001), 'Modelling the resilience of Australian savanna systems to grazing impacts', *ENVIRONMENT INTERNATIONAL* **27**(2-3 Sp. Iss. SI), 167-172.

Martin, S. (2004), 'The cost of restoration as a way of defining resilience: a viability approach applied to a model of lake eutrophication', *ECOLOGY AND SOCIETY* **9**(2).

Ortiz, M. & Wolff, M. (2002), 'Dynamical simulation of mass-balance trophic models for benthic communities of north-central Chile: assessment of resilience time under alternative management scenarios', *ECOLOGICAL MODELLING* **148**(3), 277-291.

Pawlowski, C. W, and C. McCord. 2009. “A Markov Model for Assessing Ecological Stability Properties.” Ecological Modelling 220 (2): 86–95.

Perez-Espana, H. & Arreguin-Sanchez, F. (2001), 'An inverse relationship between stability and maturity in models of aquatic ecosystems', *ECOLOGICAL MODELLING* **145**(2-3), 189-196.

Peterson, G. (2002), 'Estimating resilience across landscapes', *CONSERVATION ECOLOGY* **6**(1).

Popp, A., S. Domptail, N. Blaum, and F. Jeltsch. 2009. "Landuse Experience Does Qualify for Adaptation to Climate Change." Ecological Modelling 220 (5): 694–702.

Ranjan, R.; Marshall, E. & Shortle, J. (2008), 'Optimal renewable resource management in the presence of endogenous risk of invasion', *Journal Of Environmental Management* **89**(4), 273--283.

Samhouri, J. F, P. S Levin, and C. H Ainsworth. 2010. "Identifying Thresholds for Ecosystem-based Management." PLoS One 5 (1): e8907.

Satake, Akiko, Yoh Iwasa, and Simon A. Levin. 2008. "Comparison Between Perfect Information and Passive–adaptive Social Learning Models of Forest Harvesting." Theoretical Ecology 1 (4): 189–197. doi:10.1007/s12080-008-0019-z.

Schlüter, M. & Pahl-Wostl, C. (2007), 'Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin', *ECOLOGY AND SOCIETY* **12**(2).

Schlüter, Maja, Heather Leslie, and Simon Levin. 2009. "Managing Water-use Trade-offs in a Semi-arid River Delta to Sustain Multiple Ecosystem Services: a Modeling Approach." Ecological Research 24 (3) : 491–503. doi:10.1007/s11284-008-0576-z.

Sengupta, N. (2006), 'Fragmented landholding, productivity, and resilience management', *ENVIRONMENT AND DEVELOPMENT ECONOMICS* **11**(4), 507-532.

Serrat-Capdevila, A., A. Browning-Aiken, K. Lansey, T. Finan, J. Valdés, and others. 2009. "Increasing Social–ecological Resilience by Placing Science at the Decision Table: The Role of the San Pedro Basin (Arizona) Decision-support System Model." Ecology and Society 14 (1): 37.

Thorsen, B. & Helles, F. (1998), 'Optimal stand management with endogenous risk of sudden destruction', *FOREST ECOLOGY AND MANAGEMENT* **108**(3), 287-299.

van Apeldoorn, Dirk F., Kasper Kok, Marthijn P. W. Sonneveld, and Tom (A) Veldkamp. 2011. "Panarchy Rules: Rethinking Resilience of Agroecosystems, Evidence from Dutch Dairy-Farming." Ecology and Society 16 (1).

Section 2: List of categories used for the analysis of the published models (from 1998-2011)

Criteria describing field of application and model purpose

A Type of Ecosystem

1. rangeland
2. forest
3. coral reef
4. fisheries
5. lake eutrophication
6. agriculture
7. land management (general)
8. water management (general)
9. not specified

B Type of Social System

1. Single manager
2. Several managers not interacting with each other
3. Social manager
4. Network of actors
5. Actors not specified

C Model purpose

1. system understanding
2. forecasting or prediction (in quantitative manner)
3. management or decision support (in specific context, with management recommendations)
4. communication (to management)
5. learning (model used to change mental models)

Criteria describing model formulation, complexity and model solution

E Type of model

1. difference and differential equation model
2. rule-based model
3. state and transition model

F Model complexity

1. general model/conceptual model
2. site/context-specific

G Number of model parameters

1. low (<5)

2. medium (5<p<15)
3. high (>15)

M Dynamics

1. deterministic
2. stochastic

Criteria describing space and time

I Spatial Scale

1. local
2. regional
3. global

J Time

1. not dynamic
2. dynamic with continuous time
3. dynamic with discrete time

O Type of disturbance and change

1. variability in environmental variables
2. shocks in environmental variables (e.g. droughts)
3. changes in anthropogenic variables, e.g. management
   Note: More in the sense of abrupt shocks

P Feedbacks between social and ecological system

1. no
2. yes

Criteria which represent the link to real world and the level of integration

R Uncertainty

1. not considered
2. considered

T Model validation

1. no

2. yes

U Sensitivity analysis

1. no
2. yes

Z Model limits

1. discussed
2. not discussed

AA Link to “real world”

1. parameterized with empirical data
2. validated with empirical data / pattern
3. application for management discussed
4. no link

Criteria related to resilience theory

V Resilience concept

1. resilience = return time to equilibrium (“technical resilience”)
2. resilience = capacity of system to maintain structure and function when disturbed
3. other use of resilience term
4. not specified

W Resilience Mechanism

1. buffer in system structure
2. response diversity
3. functional diversity
4. heterogeneity
5. time lags
6. cross scale effect
7. adaptive capacity of management
8. others
9. not specified

X Measures of resilience

1. return time to equilibrium
2. size of basin of attraction
3. position of system in relation to threshold
4. performance indicators (productivity)
5. others
6. not specified

Y Additional considered aspects of resilience

1. adaptive cycle
2. panarchy (cross scale interactions)
3. adaptability
4. transformability
5. slow and fast variables
6. memory effect
7. thresholds

Section 3: Historical use of modeling in resilience research

Table A1: Results of the review of 52 models of resilience from 1998-2011

Study aims	Purpose of the model	# of papers	Key insights
Understanding SES persistence	System understanding Assessment of resilience of a specific system	**6**	Few models include feedbacks between social and ecological system Social system often not specified (e.g. only represented as variable that drives the ecological system)
	Identification of system characteristics and mechanisms that determine persistence • buffer • response diversity • governance or network structure • connectivity	**11**	
	Development of methods to operationalize and analyze resilience; predict critical transitions	**6**	
	Development of measures to quantify resilience or indicators of critical transitions	**5**	
Managing SES persistence	Decision/Management support Evaluation of management strategies	**13**	Lack of explicit links with real world (validation, uncertainty analysis, sensitivity analysis) Only few studies look at robust strategies
	• Explorative assessment of alternative management measures	10	
	• Assessing the tradeoff between resilience and economic productivity	3	
	Development of optimal management strategies	**7**	
Understanding and managing adaptation and transformation	Model purpose: System understanding Understanding adaptive capacity and traps	**4**	Only few studies address adaptation of social system to change No study addresses transformation

Detailed results of the review

Social-ecological systems considered and integration of the ecological and social subsystems

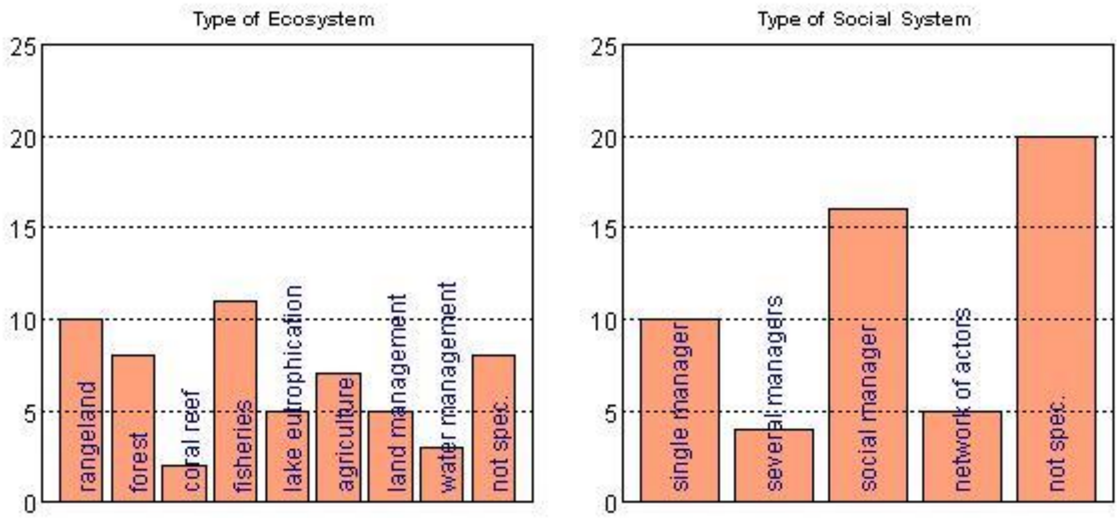

Figure A2: Ecological system/resource system (a) and social systems (b) regarded (Scale: number of papers out of all papers included in review (52))

The investigation shows that modeling studies about resilience have been developed for all different types of ecosystems or resource systems (rangeland, forest, coral reefs, fisheries, lakes, agriculture, land management and water management) (cf. Figure A2a). However, the social system is often not further specified (cf. Figure A2b), but rather represented as a change in a driving variable that is implicitly caused by change in management. Apart from that 31% of the studies assume a social manager and 19% a single one. Only in few cases a network of actors is considered (e.g. Bodin and Norberg (2005)).

The majority of studies (57%) consider feedbacks between social and ecological systems. However it is revealed that the inclusion of feedbacks varies for different model types: Social-ecological feedbacks are more present in the generic models (62%) compared to context-specific models (50%). Furthermore social-ecological feedbacks are more often included in models that apply differential or difference equations (64.0%) compared to rule-based (40%) and state and transition models (45%) (no figure).

Investigating whether disturbance is caused by anthropogenic or ecological variables the following results were depicted. In 25% of the papers disturbance was caused by variability in environmental variables, 35% caused by shocks in environmental variables and 69% caused by changes in anthropogenic variables (cf. Figure A3).

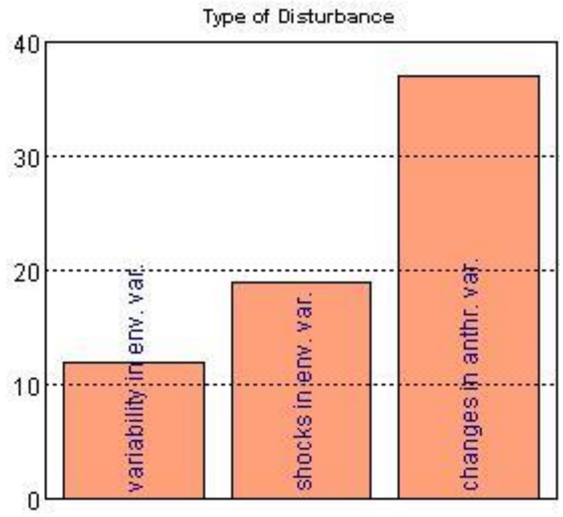

Figure A3: Types of disturbances represented in the models (Scale: number of papers out of all papers included in review (52))

Modelling techniques and system representation

Regarding the model type, the review process revealed that the majority (75%) of the studies used difference and differential equation to formulate the model, 19% used rule based models and 21% state and transition models (multiple answers possible, e.g. Bodin 2005 used differential equation to describe the ecological model and multi-agent simulation for the social system).

46% of the studies are stochastic. All models are formulated in a dynamic manner: 58% with continuous time, 42% with discrete time. From the spatial scale point of view: 67% addressed a local problem and 31% a regional. Two studies addressed a global scale.

Another focus of our review was set on whether the model built is context specific or is rather of general character (generic). The majority of the model studies used a generic model (67%). 35% of the models where context-specific (double entries were possible.) In a first specification, we wanted to investigate, whether a context-specific study uses another model description (rule-based vs. purely analytical) than a general one. Our review showed the following: Most general models were described by difference or differential equations (77%), secondly 18% by state-and transition models and 5% by rule-based models. Context-specific models are priorly formulated by rule-based models (38%) and 43% by equation-based approaches and 19% by state-and-transition models.

In a second specification, we wanted to investigate, if the utilization of context-specific vs. general model approach depends on the model purpose. We revealed the following: Models that address management issues, aim at forecast or support communication are rather context-specific than general and beside from that more complex (via number of parameters) compared to models with purpose understanding (Figures A4b, c). Consequently more than 50% of the management support models have high number of parameters, while most of the system understandings models have medium numbers. There are only very few models with a low number of parameters (in system understanding) (Fig. A4c).

A further difference in system representation depended on the modeled resource system: In rangeland, forest, fisheries, agriculture, land and water management there are both general and context-specific models. However for lake eutrophication, coral reef and studies where the type of ecosystem is not specified exclusively general models were used. Apart from coral reef, different all model types appear for the resource systems. State and transition models are not as common, mainly used in models about rangelands, forests and in models where the resource system is not specified.

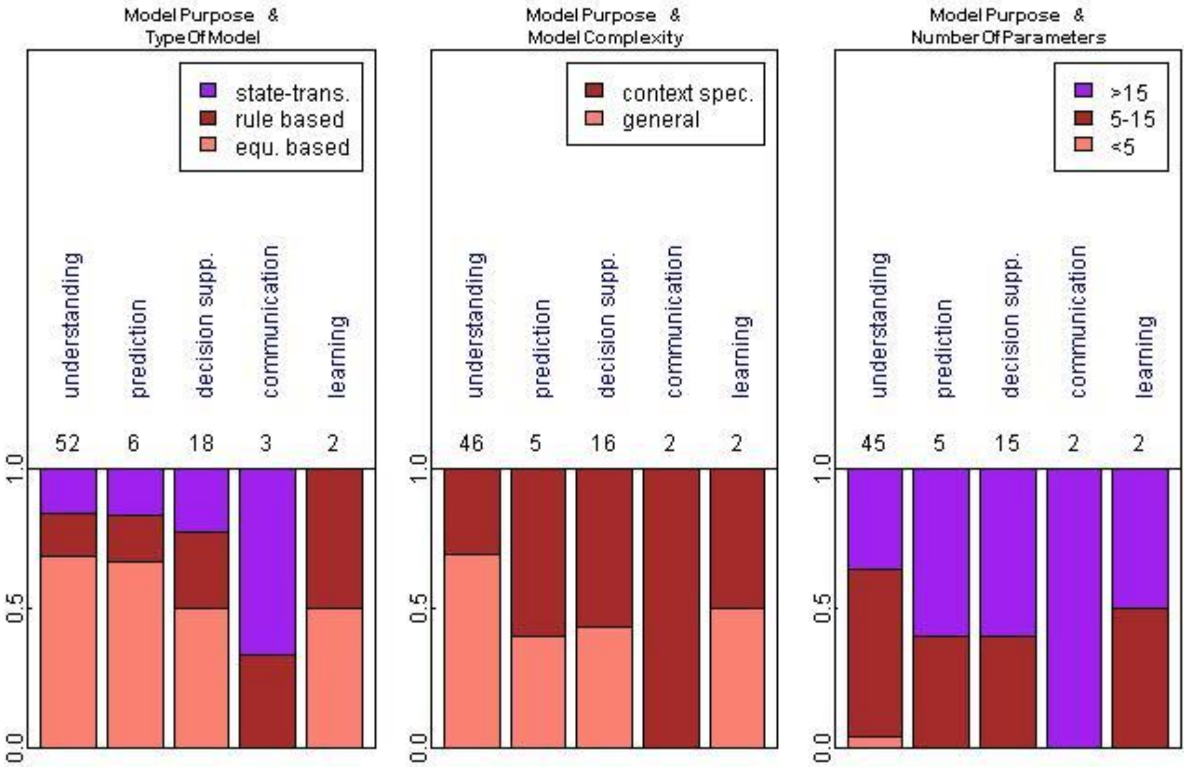

Figure A4: Relationship between model purpose and modeling technique (a) model type, b) model complexity and c) number of parameters used).