Appendix 1. Supporting online material

Results of literature search

Table A1. Hits found in the systematic literature search

Journal name	Number of hits for search term: machine learning (ML)	Number of hits for search term: deep learning	Number of hits for search term: neural network	Sum of hits for all search terms	Actual hits after screening; i.e., using ML for natural resource management
Ecology & Society	0	12	1	13	1
International Journal of the Commons	8	16	18	42	0
Sustainability	80	28	137	245	8
Ecological Modeling	219	3	541	763	2
Global Environmental Change	13	4	14	31	1
World Development	10	3	7	20	1
Journal of Environmental Management	103	2	219	324	0
Journal of Cleaner Production	199	75	580	854	0
Environmental Modeling and Software	311	35	500	846	4

PLoS ONE	38+201	66 + 9	653+144	757 + 354	6
Proceedings of the National Academy of Science (PNAS)	137+438	51 +209	188 + 205	376 + 852	0
Proceedings of the Royal Society B	59 + 71	11+ 25	52 +117	122 + 213	2
Nature	13 + 57	3+21	6 + 58	22 + 136	3
Science	38 + 88	1 + 22	18+34	57 + 144	1
Nature Methods	2+26	0+24	2+27	4+77	0
Nature Climate Change	4+17	25+44	1+5	30+66	0
Nature Sustainability	5+13	20+32	0+4	25+49	1

Note*:* The first number in a cell indicates the hits for “social ecological”; the second number indicates “natural resource”.

Overview of all articles using machine learning methods

Table A2. Overview of all articles using machine learning (ML) methods on a topic in natural resource management

NN = artificial neural network; RF = random forest; SVM = support vector machine; RFL = reinforcement learning; ABM = agent-based modeling; BRT = boosted regression trees; MRT = multivariate regression trees

Authors	Year	DOI	Topic	Type of ML used	Journal
Adisa et al.	2019	https://doi.org/10.3390/su11041145	Predict Maize Production in South Africa	NN	Sustaina-bility
Alvarez-Romero et al.	2015	https://doi.org/10.1371/journal.pone.0145574	Estimate Probability of land use change and river plumes	NN	PLoS ONE
Arima	2016	https://doi.org/10.1371/journal.pone.0152058	Simulate impact of road constructio n on deforestatio n and quantify carbon emissions	Bayesian probit land change model	PLoS ONE
Cao et al.	2019	https://doi.org/10.3390/su11195376	Short-Term Forecast of Land Use Change	NN (Recurre nt)	Sustaina-bility
Cenek et al.	2017	https://doi.org/10.1016/j.ecolmodel.2017.06.024	Machine learning evolved agent behaviors for	ABM	Ecological modelling

			fishermen		
Crespo et al.	2018	https://doi.org/10.1126/sciadv.aat3681	Classify fishing effort	BRT	Science
De Souza	2018	https://doi.org/10.1016/j.ecolmodel.2018.08.015	Model spatial distribution of deforestation	Maximum Entropy	Ecological modelling
Dreyfus-Leon et al.	1999	https://doi.org/10.1016/S0304-3800(99)00109-X	Model fishermen search behaviour	NN + RFL	Ecological modelling
Ekasingh et al.	2009	https://doi.org/10.1016/j.envsoft.2009.02.015	Predict crop choice	Decision trees	Environ-mental Modeling and Soft-ware
Fan et al.	2018	https://doi.org/10.1371/journal.pone.0198171	Predict the effectiveness of farmland consolidation	SVM	PLoS ONE
Farrell et al.	2019	https://doi.org/10.1038/s41467-019-11106-y	Simulate Exploratory strategies in fishers	RF	Nature
Frey et al.	2014	https://doi.org/10.1016/j.worlddev.2014.01.034	Predict legal security, institutional fairness and other factors in irrigation systems and fisheries	NN	World Develop-ment
Frey et al.	2013	https://doi.org/10.5751/ES-05202-180240	Model success factors in	NN	Ecology & Society

			social-ecological systems		
Gasche et al.	2013	https://doi.org/10.1371/journal.pone.0077566	Predict populations of sole and plaice to control fish harvesting	RF	PLoS ONE
Gutierrez et al.	2011	https://doi.org/10.1038/nature09689	Predict success factors for fisheries	RF	Nature
Jouffray	2019	https://doi.org/10.1098/rspb.2018.2544	Estimate relative influence of human and environmental variables in shaping reef ecosystems	BRT	Proceedings of the Royal Society B
Keane et al.		https://doi.org/10.1038/s41893-019-0458-0	Impact of wildlife management areas on community wealth	Bayesian Network	Nature Sustainability
Li et al.		http://dx.doi.org/10.1016/j.envsoft.2017.07.016	Predict sponge species richness	RF, GLM	Environmental Modeling and Software
Lindkvist	2017	https://doi.org/10.1098/rspb.2016.2762	Estimate performance of different management strategies	RFL	Proceedings of the Royal Society B
Little et al.	2007	https://doi.org/10.1016/j.ecolmodel.2007.01.013	Simulate agents harvesting a renewable	ABM + Bayesian Network	Ecological modelling

			resource		
Magierowski et al.	2015	https://doi.org/10.1371/journal.pone.0120901	Identify land-use drivers of changes in river condition	NN	PLoS ONE
Maldonado et al.	2018	https://doi.org/10.3390/su10114312	Comparison of ML-methods to select socioeconomic indicators in cultural landscapes	Various (NN, RF, Bayesian networks)	Sustainability
Mayfield et al.	2017	http://dx.doi.org/10.1016/j.envsoft.2016.10.006	Predict deforestation	Various (GLM, Bayesian Network, NN, …)	Environmental Modeling and Software
Nguyen et al.	2019	https://doi.org/10.3390/su11133615	Predict soil erosion	RF	Sustainability
Ouyang et al.	2019	https://doi.org/10.3390/su11226416	Identify ecological security patterns	Bayesian Network Machine Learning	Sustainability
Robinson et al.	2020	https://doi.org/10.1016/j.envsoft.2020.104781	Early warning detection of water supply vulnerability	Various	Environmental Modeling and Software
Romulo et al.	2018	https://doi.org/10.1038/s41467-018-06538-x	Predict investments in watershed services (IWS) programs	RF	Nature
Saputra et	2019	https://doi.org/10.3390/su11113024	Predict land use and	NN	Sustaina-

al.			land cover changes		bility
Vaclavik et al.	2013	https://doi.org/10.1016/j.gloenvcha.2013.09.004	Classify land system archetypes	NN (Self-organizing map)	Global Environ-mental Change
Woo et al.	2019	https://doi.org/10.3390/su11123397	Measure ecosystem health	RF	Sustaina-bility
Yates et al.	2016	https://doi.org/10.1371/journal.pone.0155634	Model fish species richness and abundance of fish functional groups	BRT and MRT	PLoS ONE
Zhang et al.	2018	https://doi.org/10.3390/su10124600	Predict long-term water system adaptation planning	NN	Sustaina-bility

Description of parameters

Table A3. Description of parameters varied during grid-search for model-optimization for three machine learning algorithms

Method	Parameter	Description	Range varied	Optimum
Generalized linear model	Lambda	controls amount of regularization	0-1	0.4
	Alpha	controls distribution between l1 and l2 penalties	0-1	0
Gradient boosting	Number of trees		50-2.500	1900
	Sample rate	% data sampled (for generalization)	0.4-1.0	0.85
	Max. depth	deepness of tree	5-15	6
	Column sample rate	Number of columns sampled for each split	0.2-0.5	0.32
	Column sample rate per tree	column sampling rates per tree	0.2-0.7	0.44
Shallow neural networks	Epochs	Number of cycles on the training set	30-500	305
	Learning rate	Step size in gradient descent optimization	0.001-0.3	0.15
	Number of hidden neurons	number of neurons in calculating layer	10-500	391
Deep neural networks	Epochs	as above	30-500	403
	Learning rate	as above	0.001-0.3	0.12
	Number of hidden layers	number of calculating layers	2-4	4
	Number of hidden neurons	as above	10-500	492-13-85-111

Variables in Ecological Success

Table A4. Common-pool resouces – Description of variables ecological success consists of

Variable name	Type of data	Short description
loc_ENDDATE	Number	Begin and End date (end)
opl_BEGDATE	Number	Begin and End date (beginning)
Opl_BMARKETS	Likert scale	How are the appropriated units disposed of (beginning)?
opl_CONDITON	Likert scale	Physical condition of the system
opl_EAVERAGE	Number	Average age of the units withdrawn from this resource at the end
opl_EAVERSIZ	Number	Average size of the units withdrawn from this resource at the end
opl_ECONEFF	Likert scale	Short-run Economic Technical Efficiency
opl_effindc	Text	Indicators and means of increasing efficiency
Opl_EMARKETS	Likert scale	How are the appropriated units disposed of (end)?
opl_ENDBLNC	Likert scale	Balance between quantity of units withdrawn and number available (end)
opl_ENDCONDA	Likert scale	How well-maintained is the appropriation resource (end)?
opl_ENDCONDD	Likert scale	How well-maintained is the distribution resource (end)?
opl_ENDCONDP	Likert scale	How well-maintained is the production resource (end)?
opl_ENDDATE	Number	Beginning and ending of the operational level
opl_ENDNTFER	Likert scale	Interference between technology and processes for other resources (end)
opl_ENDPOLL	Likert scale	Problems of pollution (end)
opl_ENDQUAL	Likert scale	Quality of units being withdrawn (end)
opl_ENDRATE1	Number	Volume of withdrawal for fisheries (end)
opl_ENDRATE3	Number	Volume of withdrawal for irrigation (end)

opl_ENDTECHX	Likert scale	Extent of technical externalities (end)
opl_ESEXDEVL	Likert scale	Are the units sexually mature at this size or age (end)?
opl_Evaluate	Text	Brief synopsis of how this system is evaluated (performance)
opl_MTONHA	Number	Metric tons of agricultural product per year per hectare
opl_NEWTECH	Likert scale	Is new technology introduced?
opl_NEWVALUE	Likert scale	External change in exchange value of units appropriated?
opl_ONEMARKT	Likert scale	Do appropriators sell this unit in more than one market?
opl_TAILEND	Likert scale	Adequacy and predictability of water to tailenders
opl_TECHEFF	Likert scale	Technical Effectiveness of water availability
opl_TYPRESUL	Text	Evaluation of results
res_MULTAPPR	Likert scale	Relationship among multiple appropration processes
res_WHENBILT	Number	Date of construction of system
sbg_LGTHUSE	Likert scale	Length of time this subgroup has regularly appropriated
scr_paragrph	Text	Abstract of document being screened

Variable – to – Concept Mapping for the common-pool resources data

Variable Name	Mapped to concept	Variable Name	Mapped to concept
loc_LOCDSCPT	Resource size	ors_Membappr	Participation of users
loc_LOCSIZE	Resource size	ors_Orgparag	Participation of users
opl_endrate2	Resource size	res_DISTHEAD	Participation of users
res_APPRESRC	Resource size	res_DISTOPER	Participation of users
res_BRANCHES	Resource size	res_DISTSAME	Participation of users
res_LENGTH	Resource size	res_HEADOPER	Participation of users
res_LNTHBRCH	Resource size	res_HEADSAME	Participation of users
res_LNTHMAIN	Resource size	res_SECTOR2	Participation of users

res_METHEAD1	Resource size	res_SELEDIST	Participation of users
res_METHEAD2	Resource size	res_SELPROD	Participation of users
res_STOREVOL	Resource size	sbg_MANAGE	Participation of users
res_SURFAREA	Resource size	sbg_PROnurul	Participation of users
res_SYSTAREA	Resource size	scr_TYPE	Participation of users
scr_Slocsize	Resource size	sbg_WITHDRAW	Legal certainty and legitimacy
loc_LOCBOUND	Resource boundaries	loc_ENDDATE	Legal certainty and legitimacy
loc_LOCDSCPT	Resource boundaries	loc_FREQCOMM	Legal certainty and legitimacy
opl_RECORDav	Resource boundaries	loc_jurinam1	Legal certainty and legitimacy
opl_RECORDwi	Resource boundaries	loc_jurinam2	Legal certainty and legitimacy
opl_USERseen	Resource boundaries	loc_locjuris	Legal certainty and legitimacy
res_BOUNDAR2	Resource boundaries	loc_ONECOUNT	Legal certainty and legitimacy
res_BOUNDAR3	Resource boundaries	Opl_BFORMOWN	Legal certainty and legitimacy
res_BOUNDAR4	Resource boundaries	opl_BRIBERY	Legal certainty and legitimacy
res_DESCRIPT	Resource boundaries	opl_duration	Legal certainty and legitimacy
res_DISTAPPR	Resource boundaries	opl_Enddate	Legal certainty and legitimacy
res_OFFNUM	Resource boundaries	opr_DEFpay	Legal certainty and legitimacy
res_PRODAPPR	Resource boundaries	opr_natcolch	Legal certainty and legitimacy
res_PRODDIST	Resource boundaries	opr_regcolch	Legal certainty and legitimacy
res_PRODLOCA	Resource boundaries	opr2_LEGITIM	Legal certainty and legitimacy
loc_LOCDSCPT	Accessibility	ors_Begdate	Legal certainty and legitimacy
opr2_seasonln	Accessibility	ors_Conelect	Legal certainty and legitimacy
res_AVGACCES	Accessibility	ors_Enddate	Legal certainty and legitimacy
res_STEEP	Accessibility	ors_Expother	Legal certainty and legitimacy
sbg_RESIDENT	Accessibility	ors_Expown	Legal certainty and legitimacy
loc_BEGDATE	Ecological success at the beginning	ors_Extremov	Legal certainty and legitimacy
opl_BAVERSIZ	Ecological success at the beginning	ors_Extrep	Legal certainty and legitimacy

opl_BEGBLNC	Ecological success at the beginning			res_DISPUTE	Legal certainty and legitimacy
opl_BEGCONDA	Ecological success at the beginning			res_DONATION	Legal certainty and legitimacy
opl_BEGCONDD	Ecological success at the beginning			res_DONOR	Legal certainty and legitimacy
opl_BEGCONDP	Ecological success at the beginning			sbg_EQIPshar	Legal certainty and legitimacy
opl_BEGNTFER	Ecological success at the beginning			sbg_TRANflow	Legal certainty and legitimacy
opl_BEGPOLL	Ecological success at the beginning			sbg_TRANshar	Legal certainty and legitimacy
opl_BEGQUAL	Ecological success at the beginning			loc_FREQCOMM	Administration
opl_BEGRATE1	Ecological success at the beginning			ors_Execappr	Administration
opl_BEGRATE2	Ecological success at the beginning			ors_Execinc	Administration
opl_BEGRATE3	Ecological success at the beginning			ors_EXECOTHR	Administration
opl_BEGTECHX	Ecological success at the beginning			ors_Execown	Administration
opl_BSEXDEVL	Ecological success at the beginning			ors_Execpaid	Administration
opl_PRIORapp	Ecological success at the beginning			ors_Execper	Administration
opl_reason	Ecological success at the beginning			ors_Offnear	Administration
res_LINED	Ecological success at the beginning			opl_GENinfo	Information
res_ANALUNIT	Manageability	opl_MAPAVAIL	Information		
res_CONTROL	Manageability	opl_MAPPROD	Information		
res_MICROZON	Manageability	opl_RADIOCOM	Information		
res_PREDVAR1	Manageability	opl_RECORDav	Information		
res_PREDVAR2	Manageability	opl_RECORDco	Information		
res_PREDVAR3	Manageability	opl_RECORDke	Information		
res_QUALBETR	Manageability	opl_RECORDla	Information		
res_RSRCUNIT	Manageability	opl_RECORDma	Information		
res_SECTOR1	Manageability	opl_RECORDmo	Information		
res_STOREVOL	Manageability	opl_RECORDph	Information		
res_SURFAREA	Manageability	opl_RECORDwi	Information		
res_TYPERES	Manageability	opl_UNDERres	Information		

res_VAROTIME	Manageability	opr_QUALUNIT	Information
res_VARSPACE	Manageability	opr2_appmonit	Information
res_VARYEAR	Manageability	opr2_appright	Information
res_WATERORI	Manageability	opr2_appwork	Information
sbg_ABSOQUAN	Regeneration of RU	opr2_condres	Information
opl_BAVERAGE	Regeneration of RU	opr2_DEFinf	Information
opl_EXTINCAP	Regeneration of RU	opr2_IOther	Information
res_POTNTIAL	Regeneration of RU	opr2_numunit	Information
sbg_OLSON	Regeneration of RU	opr2_physfact	Information
sbg_SHARCHNG	Regeneration of RU	opr2_qassets	Information
sbg_TECHEXTR	Regeneration of RU	opr2_unitflow	Information
sbg_USERATE1	Regeneration of RU	opr2_WRITTEN	Information
sbg_USErate2	Regeneration of RU	sbg_LITERACY	Information
loc_NUMHOU	Number of actors	opl_aindictc	Characteristics of rules
loc_NUMPOP	Number of actors	opr_CLEAR	Characteristics of rules
opl_BNUMAPP1	Number of actors	opr_DEFAGGR	Characteristics of rules
opl_BNUMAPP2	Number of actors	opr_EQSHARED	Characteristics of rules
opl_BNUMTEM1	Number of actors	opr_FIXNUM	Characteristics of rules
opl_BNUMTEM2	Number of actors	opr_MINSIZE	Characteristics of rules
opl_Enumapp1	Number of actors	opr_NARRANGE	Characteristics of rules
opl_enumapp2	Number of actors	opr_RTRANS2	Characteristics of rules
opl_ENUMTEM1	Number of actors	opr_rulsetsb	Characteristics of rules
opl_ENUMTEM2	Number of actors	opr_RULSETSP	Characteristics of rules
sbg_BNUMUSR1	Number of actors	opr2_A1Other	Characteristics of rules
sbg_BNUMUSR2	Number of actors	opr2_A2Other	Characteristics of rules
sbg_Enumusr1	Number of actors	opr2_aggrrule	Characteristics of rules
sbg_ENUMusr2	Number of actors	opr2_apprtax	Characteristics of rules

sbg_SNUMTEM1	Number of actors	opr2_capinv	Characteristics of rules
sbg_SNUMTEM2	Number of actors	opr2_DEFauth	Characteristics of rules
sbg_TEAMSIZE	Number of actors	opr2_easyund	Characteristics of rules
scr_SNUMapp2	Number of actors	opr2_ELABsubs	Characteristics of rules
opl_CLANID	Group composition	opr2_emerglab	Characteristics of rules
opl_Families	Group composition	opr2_fixorder	Characteristics of rules
opl_RACEID	Group composition	opr2_fixperc	Characteristics of rules
opl_SG1TOSG2	Group composition	opr2_fixtime	Characteristics of rules
opl_SG2TOSG3	Group composition	opr2_FLEXIBLE	Characteristics of rules
opl_SG3TOSG4	Group composition	opr2_freewith	Characteristics of rules
sbg_Sbgpdes	Group composition	opr2_maintlab	Characteristics of rules
sbg_Scaste1	Group composition	opr2_ncycles	Characteristics of rules
sbg_SCLANID1	Group composition	opr2_RULEdur	Characteristics of rules
sbg_Scultvwr	Group composition	opr2_rulsetsa	Characteristics of rules
sbg_Sethid1	Group composition	opr2_sploc	Characteristics of rules
sbg_Sgender1	Group composition	opr2_spseason	Characteristics of rules
sbg_Sgender2	Group composition	ors_Admlevel	Characteristics of rules
sbg_Slang1	Group composition	ors_Ruleclas	Characteristics of rules
sbg_Sothcomm	Group composition	sbg_EQIPshar	Characteristics of rules
sbg_SRACEID1	Group composition	sbg_TRANflow	Characteristics of rules
sbg_Srelid1	Group composition	sbg_TRANshar	Characteristics of rules
opl_BEGTRUST	Social capital	opl_Basis	Fairness
opl_ENDtrust	Social capital	opl_REALoser	Fairness
opl_GENRELtn	Social capital	opl_Realyes	Fairness
opr2_howtran	Social capital	opl_RELequty	Fairness
opr2_LABorg	Social capital	opl_SG1TOSG3	Fairness
ors_Addserv	Social capital	opl_SG1TOSG4	Fairness

ors_Services	Social capital	opl_SG2TOSG4	Fairness
res_WHOBUILT	Social capital	opl_WORSToff	Fairness
sbg_ENTACT	Social capital	opr_UNEQprib	Fairness
sbg_LISTPROB	Social capital	opr_UNEQPUN	Fairness
sbg_OFFSPRNG	Social capital	opr_UNEQrew	Fairness
sbg_Sbgpdes	Social capital	opr2_FAIR	Fairness
sbg_TEAMBASE	Social capital	opr2_UNEQduta	Fairness
sbg_TECHUSED	Social capital	opr2_UNEQpria	Fairness
opl_BRENTDIS	Dependency on resource	ors_Expown	Fairness
opl_ERENTDIS	Dependency on resource	sbg_MAINCONT	Fairness
loc_PERMPOP	Dependency on resource	sbg_SUBvar	Fairness
opl_INSURANC	Dependency on resource	opl_guard	Control
opl_insurdes	Dependency on resource	opl_monpaid	Control
opl_Labor	Dependency on resource	opl_OFFpgrd	Control
opl_labrdays	Dependency on resource	opl_OffpNum	Control
opl_MAINTres	Dependency on resource	opl_PEAKgrd	Control
opl_Penalty	Dependency on resource	opl_PeakNum	Control
opr_PRICESUP	Dependency on resource	opl_RLEVEL	Control
opr_SUMFEES1	Dependency on resource	opl_SELFmon	Control
opr_SUMFEES2	Dependency on resource	opl_USERseen	Control
opr_WAGEUSE	Dependency on resource	opr_ADJOINFD	Control
ors_Fisource	Dependency on resource	ors_Expown	Control
ors_Orgparag	Dependency on resource	res_CONTROL	Control
res_IMPROVED	Dependency on resource	opl_aindictc	Compliance
sbg_ALTSUPLY	Dependency on resource	opl_BRIBERY	Compliance
sbg_ASSETS	Dependency on resource	opl_MONsanct	Compliance
sbg_AVERinc	Dependency on resource	opl_Penalty	Compliance

sbg_AVOIDhrm	Dependency on resource	opl_PHYsanct	Compliance
sbg_ENHANCE	Dependency on resource	opl_SOCsanct	Compliance
sbg_FAMINCDE	Dependency on resource	opl_VARsanct	Compliance
sbg_KPRESURE	Dependency on resource	opr_DEFpay	Compliance
sbg_LONGvar	Dependency on resource	opr_FINES	Compliance
sbg_OWNlabor	Dependency on resource	opr_INCARCER	Compliance
sbg_SUBalt1	Dependency on resource	opr_LOSEentr	Compliance
sbg_SUBALT2	Dependency on resource	opr_SHUNNING	Compliance
sbg_SUBnot	Dependency on resource	opr2_LEGITIM	Compliance
sbg_SUBSIM	Dependency on resource	ors_Enfrule	Compliance
sbg_TEAMCAP	Dependency on resource	ors_Expown	Compliance
opl_OTHRcoop	Dependency on group	sbg_RULEbrak	Compliance
opr_shareorg	Dependency on group	sbg_RULEfoll	Compliance
ors_Fisource	Dependency on group	sbg_RULquanc	Compliance
ors_Orgparag	Dependency on group	sbg_RULtechc	Compliance
sbg_ENTACT	Dependency on group	sbg_RULtimec	Compliance
sbg_OFFSPRNG	Dependency on group	ors_Expown	Conflict management
opl_NONapp	Group boundaries	res_CONFLICT	Conflict management
opl_Numnon1	Group boundaries	sbg_Sbgpdes	Conflict management
opl_NUMnon2	Group boundaries	sbg_VIOLENC1	Conflict management
opl_WELLdefn	Group boundaries	sbg_VIOLENC2	Conflict management
opr_AGE	Group boundaries	opr_LOSEentr	Exclusion
opr_auction	Group boundaries	res_SHARED	Exclusion
opr_BOther	Group boundaries	sbg_EXCLUDED	Exclusion
opr_caste	Group boundaries	opl_BOWNCLOS	Exclusion
opr_CITCOUNT	Group boundaries	opl_EOWNCLOS	Exclusion
opr_citlocal	Group boundaries	opl_BAPCLOSE	Exclusion

opr_CITSUBDI	Group boundaries	opl_EAPCLOSE	Exclusion
opr_CLAN	Group boundaries	sbg_ACCESS	Exclusion
opr_CLASS	Group boundaries	sbg_EXCLUDIN	Exclusion
opr_conusage	Group boundaries	opl_NEWGROUP	Exclusion
opr_DEFbound	Group boundaries	opl_EXTPOLL	Relations
opr_DEMSKILL	Group boundaries	loc_RESCONF	Relations
opr_ELIGIBLE	Group boundaries	opl_Bapclose	Relations
opr_ENTRYFEE	Group boundaries	opl_Bownclos	Relations
opr_ethnic	Group boundaries	opl_commlang	Relations
opr_GENDER	Group boundaries	opl_Cultvwr	Relations
opr_LEVEDUC	Group boundaries	opl_Eapclose	Relations
opr_LICENSE	Group boundaries	opl_Eownclos	Relations
opr_LICLIMIT	Group boundaries	opl_ethncid	Relations
opr_lottery	Group boundaries	opl_Newgroup	Relations
opr_organiza	Group boundaries	opl_NUMsubgp	Relations
opr_OWNAPPRO	Group boundaries	opl_Othrcomm	Relations
opr_ownland	Group boundaries	opl_relanims	Relations
opr_ownright	Group boundaries	opl_sex	Relations
opr_RACE	Group boundaries	opl_socstrat	Relations
opr_RTRANS1	Group boundaries	ors_Expother	Relations
opr_RTRANS2	Group boundaries	ors_Fisource	Relations
opr_seasfee	Group boundaries	res_DESCRIPT	Relations
opr_shareorg	Group boundaries	res_DISPUTE	Relations
opr_shareres	Group boundaries	res_DONATION	Relations
opr_unitsuse	Group boundaries	res_DONOR	Relations
opr_USETECH	Group boundaries	res_IMPROVED	Relations
sbg_Sbgpdes	Group boundaries	res_OFFNUM	Relations

sbg_WELdefin	Group boundaries	res_PARENT	Relations
opl_aindictc	Participation of users	res_PARNAME	Relations
opl_ARENAS	Participation of users	res_WHOBUILT	Relations
opl_ARENfreq	Participation of users	sbg_ACCESS	Relations
opl_NEWOPRUL	Participation of users	sbg_Excludin	Relations
opr_loccolch	Participation of users	sbg_OLSON	Relations
opr2_regcolch	Participation of users	sbg_SUBwhere	Relations
opr_RTRANS2	Participation of users	loc_ECONOLOC	Capabilities to adapt to change
ori_Lev1Act	Participation of users	opl_INSURANC	Capabilities to adapt to change
ori_Lev2Act	Participation of users	opl_insurdes	Capabilities to adapt to change
ori_Lev3Act	Participation of users	opl_reason	Capabilities to adapt to change
ori_OrgType	Participation of users	opr_EXTAID1	Capabilities to adapt to change
ors_Execappr	Participation of users	opr_EXTAID2	Capabilities to adapt to change
ors_Expown	Participation of users	opr_EXTAID3	Capabilities to adapt to change
		sbg_LONGvar	Capabilities to adapt to change
		sbg_SUBvar	Capabilities to adapt to change

LITERATURE CITED

Adisa, O., J. Botai, A. Adeola, A. Hassen, C. Botai, D. Darkey, and E. Tesfamariam. 2019. Application of Artificial Neural Network for Predicting Maize Production in South Africa. *Sustainability* 11(4):1145.

Álvarez-Romero, J. G., R. L. Pressey, N. C. Ban, and J. Brodie. 2015. Advancing Land-Sea Conservation Planning: Integrating Modelling of Catchments, Land-Use Change, and River Plumes to Prioritise Catchment Management and Protection. *PLoS ONE* 10(12):e0145574.

Arima, E. Y. 2016. A Spatial Probit Econometric Model of Land Change: The Case of Infrastructure Development in Western Amazonia, Peru. *PLoS ONE* 11(3):e0152058.

Cao, C., S. Dragićević, and S. Li. 2019. Short-Term Forecasting of Land Use Change Using Recurrent Neural Network Models. *Sustainability* 11(19):5376.

Cenek, M., and M. Franklin. 2017. An adaptable agent-based model for guiding multi-species Pacific salmon fisheries management within a SES framework. *Ecological Modelling* 360:132–149.

Crespo, G. O., D. C. Dunn, G. Reygondeau, K. Boerder, B. Worm, W. Cheung, D. P. Tittensor, and P. N. Halpin. 2018. The environmental niche of the global high seas pelagic longline fleet. *Science advances* 4(8):eaat3681.

Ekasingh, B., and K. Ngamsomsuke. 2009. Searching for simplified farmers' crop choice models for integrated watershed management in Thailand: A data mining approach. *Environmental Modelling & Software* 24(12):1373–1380.

Fan, Y., X. Jin, X. Xiang, Le Gan, X. Yang, Z. Zhang, and Y. Zhou. 2018. Evaluating and predicting the effectiveness of farmland consolidation on improving agricultural productivity in China. *PLoS ONE* 13(6):e0198171.

Frey, U. J., and H. Rusch. 2013. Using Artificial Neural Networks for the Analysis of Social-Ecological Systems. *Ecology and Society* 18(2).

Frey, U. J., and H. Rusch. 2014. Modeling Ecological Success of Common Pool Resource Systems Using Large Datasets. *World Development* 59:93–103.

Gasche, L., S. Mahévas, and P. Marchal. 2013. Supporting fisheries management by means of complex models: Can we point out isles of robustness in a sea of uncertainty? *PLoS ONE* 8(10):e77566.

Gutiérrez, N. L., R. Hilborn, and O. Defeo. 2011. Leadership, social capital and incentives promote successful fisheries. *Nature* 470(7334):386–389.

Jouffray, J.-B., L. M. Wedding, A. V. Norström, M. K. Donovan, G. J. Williams, L. B. Crowder, A. L. Erickson, A. M. Friedlander, N. A. J. Graham, J. M. Gove, C. V. Kappel, J. N. Kittinger, J. Lecky, K. L. L. Oleson, K. A. Selkoe, C. White, I. D. Williams, and M.

Nyström. 2019. Parsing human and biophysical drivers of coral reef regimes. *Proceedings. Biological sciences* 286(1896):20182544.

Jules Dreyfus-León, M. 1999. Individual-based modelling of fishermen search behaviour with neural networks and reinforcement learning. *Ecological Modelling* 120(2-3):287–297.

Keane, A., J. F. Lund, J. Bluwstein, N. D. Burgess, M. R. Nielsen, and K. Homewood. 2020. Impact of Tanzania's Wildlife Management Areas on household wealth. *Nature Sustainability* 3(3):226–233.

Li, J., B. Alvarez, J. Siwabessy, M. Tran, Z. Huang, R. Przeslawski, L. Radke, F. Howard, and S. Nichol. 2017. Application of random forest, generalised linear model and their hybrid methods with geostatistical techniques to count data: Predicting sponge species richness. *Environmental Modelling & Software* 97:112–129.

Lindkvist, E., Ö. Ekeberg, and J. Norberg. 2017. Strategies for sustainable management of renewable resources during environmental change. *Proceedings. Biological sciences* 284(1850).

Little, L. R., and A. D. McDonald. 2007. Simulations of agents in social networks harvesting a resource. *Ecological Modelling* 204(3-4):379–386.

Magierowski, R. H., S. M. Read, S. J. B. Carter, D. M. Warfe, L. S. Cook, E. C. Lefroy, and P. E. Davies. 2015. Inferring landscape-scale land-use impacts on rivers using data from mesocosm experiments and artificial neural networks. *PLoS ONE* 10(3):e0120901.

Maldonado, A., D. Ramos-López, and P. Aguilera. 2018. A Comparison of Machine-Learning Methods to Select Socioeconomic Indicators in Cultural Landscapes. *Sustainability* 10(11):4312.

Mayfield, H., C. Smith, M. Gallagher, and M. Hockings. 2017. Use of freely available datasets and machine learning methods in predicting deforestation. *Environmental Modelling & Software* 87:17–28.

Nguyen, K. A., W. Chen, B.-S. Lin, U. Seeboonruang, and K. Thomas. 2019. Predicting Sheet and Rill Erosion of Shihmen Reservoir Watershed in Taiwan Using Machine Learning. *Sustainability* 11(13):3615.

O'Farrell, S., J. N. Sanchirico, O. Spiegel, M. Depalle, A. C. Haynie, S. A. Murawski, L. Perruso, and A. Strelcheck. 2019. Disturbance modifies payoffs in the explore-exploit trade-off. *Nature communications* 10(1):3363.

Ouyang, Wang, and Zhu. 2019. Construction of the Ecological Security Pattern of Urban Agglomeration under the Framework of Supply and Demand of Ecosystem Services Using Bayesian Network Machine Learning: Case Study of the Changsha-Zhuzhou-Xiangtan Urban Agglomeration, China. *Sustainability* 11(22):6416.

Robinson, B., J. S. Cohen, and J. D. Herman. 2020. Detecting early warning signals of long-term water supply vulnerability using machine learning. *Environmental Modelling & Software* 131:104781.

Romulo, C. L., S. Posner, S. Cousins, J. Hoyle Fair, D. E. Bennett, H. Huber-Stearns, R. C. Richards, and R. I. McDonald. 2018. Global state and potential scope of investments in watershed services for large cities. *Nature communications* 9(1):4375.

Saputra, M. H., and H. S. Lee. 2019. Prediction of Land Use and Land Cover Changes for North Sumatra, Indonesia, Using an Artificial-Neural-Network-Based Cellular Automaton. *Sustainability* 11(11):3024.

Souza, R. A. de, and P. de Marco. 2018. Improved spatial model for Amazonian deforestation: An empirical assessment and spatial bias analysis. *Ecological Modelling* 387:1–9.

Václavík, T., S. Lautenbach, T. Kuemmerle, and R. Seppelt. 2013. Mapping global land system archetypes. *Global Environmental Change* 23(6):1637–1647.

Woo, S. Y., C. G. Jung, J. W. Lee, and S. J. Kim. 2019. Evaluation of Watershed Scale Aquatic Ecosystem Health by SWAT Modeling and Random Forest Technique. *Sustainability* 11(12):3397.

Yates, K. L., C. Mellin, M. J. Caley, B. T. Radford, and J. J. Meeuwig. 2016. Models of Marine Fish Biodiversity: Assessing Predictors from Three Habitat Classification Schemes. *PLoS ONE* 11(6):e0155634.

Zhang, J., D. Fu, C. Urich, and R. Singh. 2018. Accelerated Exploration for Long-Term Urban Water Infrastructure Planning through Machine Learning. *Sustainability* 10(12):4600.

Code

The following code section shows the full code in R to produce 500 models for deep neural networks with the h2o software package. Data preparation, loading and saving models and results are part of the workflow, but are not specified in detail here, since these are user specific and not part of the core machine learning code.

```
# Load libraries

library(data.table)

library(h2o)

# Load data = user+environment specific => empty


# Initialise H2O

localH2O = h2o.init(nthreads=-1, min_mem_size = "8196M", max_mem_size = "20490M")

# Convert to h2o

h2o_input <- as.h2o(input)

# Split 80:20

splits <- h2o.splitFrame(h2o_input, c(0.80,0))

train <- h2o.assign(splits[[1]], "train")

test <- h2o.assign(splits[[3]], "test")

######################

# Set Hyperparameter #

######################
```

```
# Produces architectures

number_architectures <- 20

min_neurons <- 10

max_neurons <- 500

max_nr_layers <- 4

hidden_opts = lapply(1:number_architectures,

function(x) min_neurons + sample(max_neurons, sample(max_nr_layers),

replace=TRUE))

# Select range of learn rates

min_learnrate <- 0.01

max_learnrate <- 0.30

learnrate_stepsize <- 0.005

learn_rate_opts <- seq(min_learnrate,max_learnrate, learnrate_stepsize)

# Select range of epochs

min_epochs <- 50

max_epochs <- 400

epoch_stepsize <- 5

epochs_opts <- seq(min_epochs, max_epochs, epoch_stepsize)

# Cross-validation number of folds

nfolds <- 5

hyper_params = list(

hidden = hidden_opts,
```

```
rate = learn_rate_opts,

epochs = epochs_opts

)

####################

# Set Search Criteria #

####################


maxmodels <- 500


search_criteria = list(

strategy = "RandomDiscrete", # "RandomDiscrete" vs "Cartesian"

max_models = maxmodels

)

################

# Grid Search #

################

# Run model grid

dl_grid <- h2o.grid(

algorithm = "deeplearning",

grid_id = "dlgrid",

x = predictors,

y = response,
```

```
training_frame = train,

nfolds = nfolds,

keep_cross_validation_predictions = TRUE,

model_id = "dl_grid",

hyper_params = hyper_params,

search_criteria = search_criteria

)

# Extracting and saving models and model results (user specific => not shown here)

# Shut down the H2O cluster:

h2o.shutdown(prompt = FALSE)
```