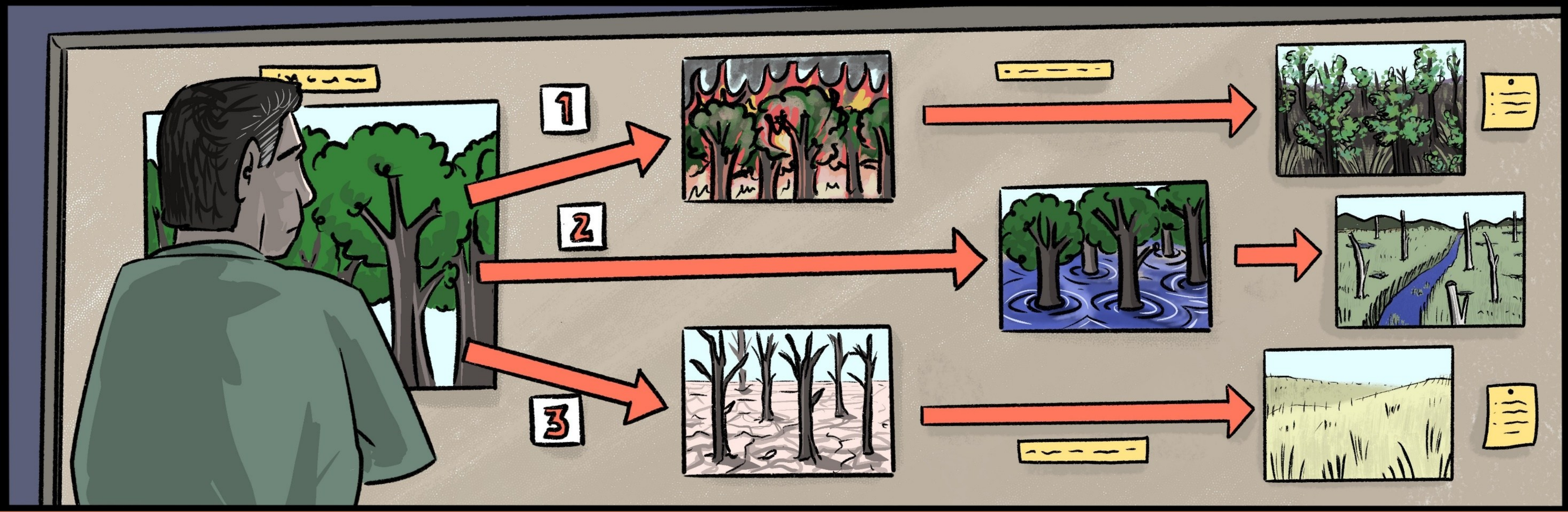


Ecological scenarios: embracing ecological uncertainty for climate change adaptation

Kyra Clark-Wolf

Project Team: Wynne Moss, Imtiaz Rangwala, Brian Miller, Helen Sofaer

NC CASC, CIRES, University of Colorado Boulder

June 12, 2025

Illustration: Benjamin Slyngstad, USGS

Acknowledgements

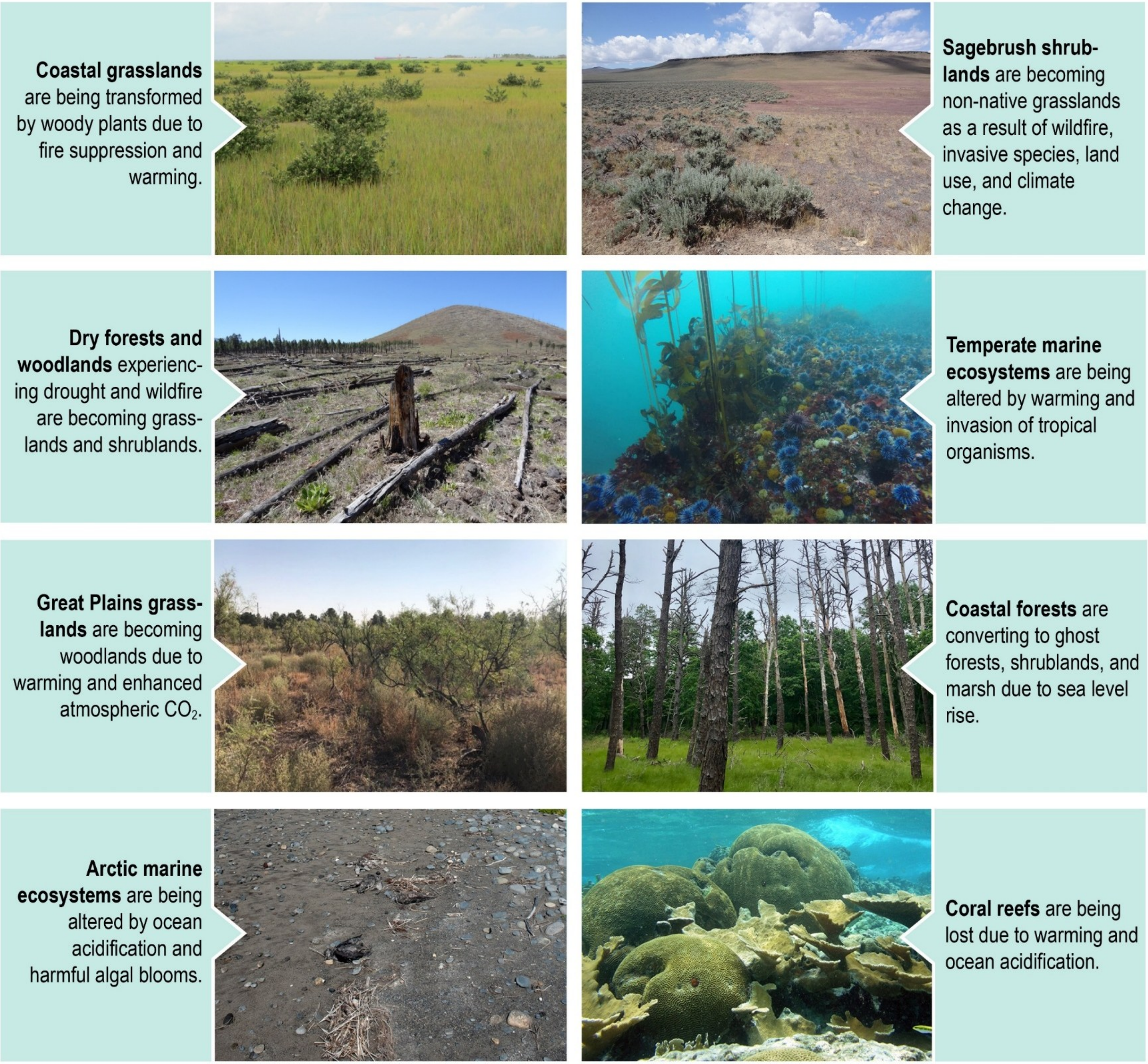
- **Funding sources:** USGS North Central Climate Adaptation Science Center
- **Ecological Scenarios Working Group:** Wynne Moss, Imtiaz Rangwala, Brian Miller, Helen Sofaer, Dawn Magness, Gregor Schuurman, Amy Symstad, Tony Ciocco, Meagan Oldfather, Joe Barsugli, Renee Rondeau, Dominique Bachelet, Shelley Crausbay, Jonathan Coop, Tyler Hoecker, Amber Runyon, Orien Richmond, Jena Lewinsohn, Robin Russell, Jennifer Wilkening, Bill Travis
- **CU Boulder NC CASC Team:** Imtiaz Rangwala, Bill Travis, Hailey Robe, Jane Wolken, Heather Yocum, Christy Miller Hesed, Ulyana Horodyskyj Pena, James Rattling Leaf, Chelsea Nagy, Laura Dee, Caitlin White
- **U.S. Fish and Wildlife Service Partners:** Orien Richmond, Steve Kettler, Jeff Runge, and many others!

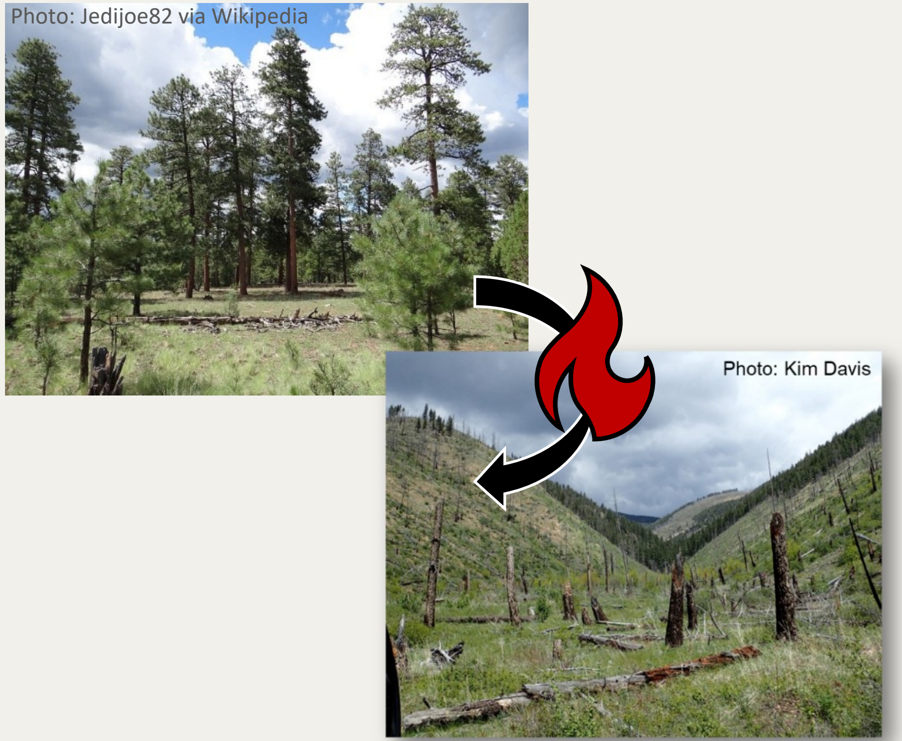
Special thanks to: Angie Moline

ECOSCENARIOS WORKING GROUP


ROAD
CLOSED
NOAA

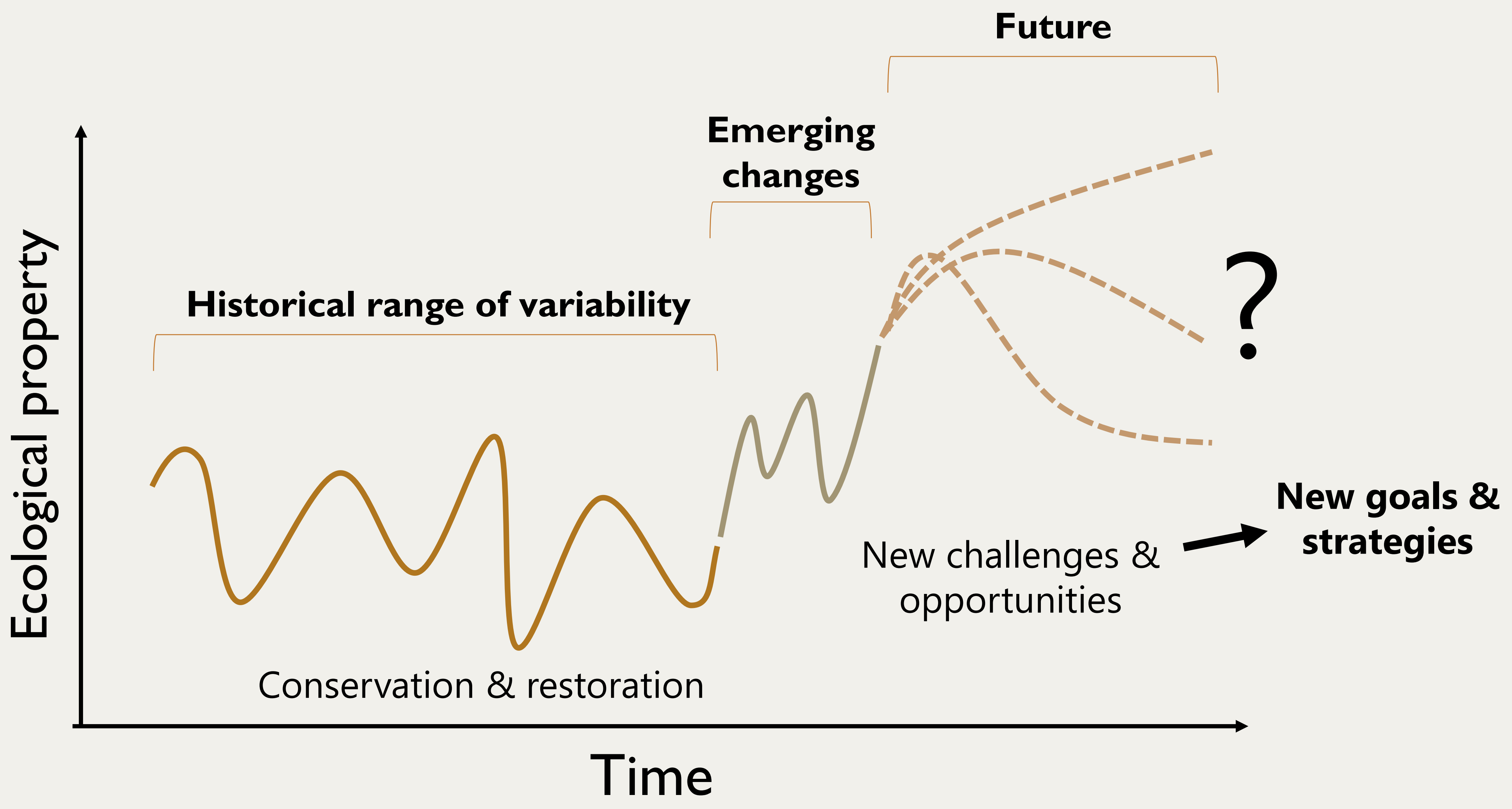
Ecological systems are rapidly transforming under climate change





Source: NCA5

Climate change adaptation seeks to manage for change



…and relies on information about future impacts

Adapted from the Fourth National Climate Assessment (2018)

What is the range of plausible futures?

Scenarios are useful when the future cannot be forecast reliably

Sources of uncertainty:

- ➢ Pace and magnitude of climate change
- ➢ Ecological responses
- ➢ Non-climate stressors

Graphic: National Park Service Climate Change Response Program

Identifying strategic management approaches under uncertainty

“No Brainers”
(staying the course)

“No Gainers”
(avoiding maladaptation)

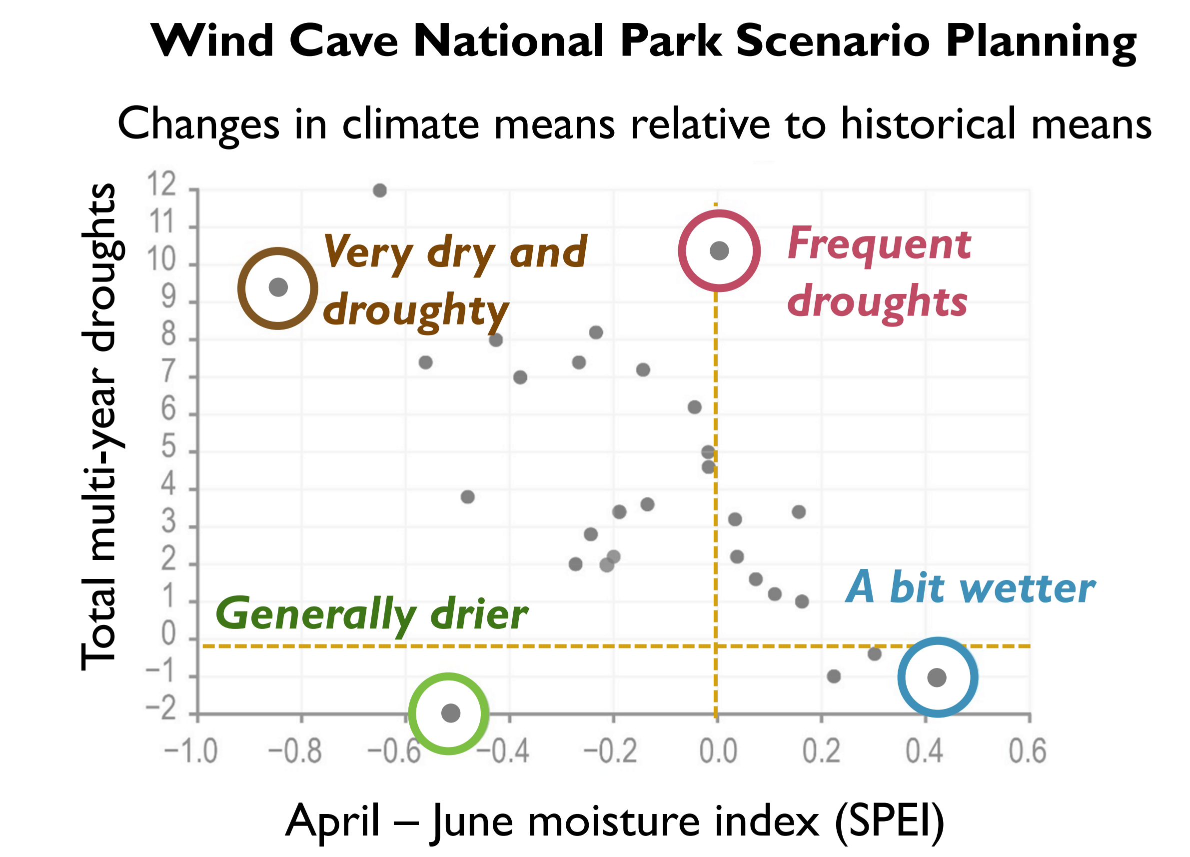
“No Regrets”
(identifying robust strategies)

“No ways”
(getting ahead of impactful possibilities)

Approaches for developing credible and useful scenarios for planning?

Graphic: National Park Service Climate Change Response Program

Climate uncertainty in scenario development: current state of practice



Scenarios are:

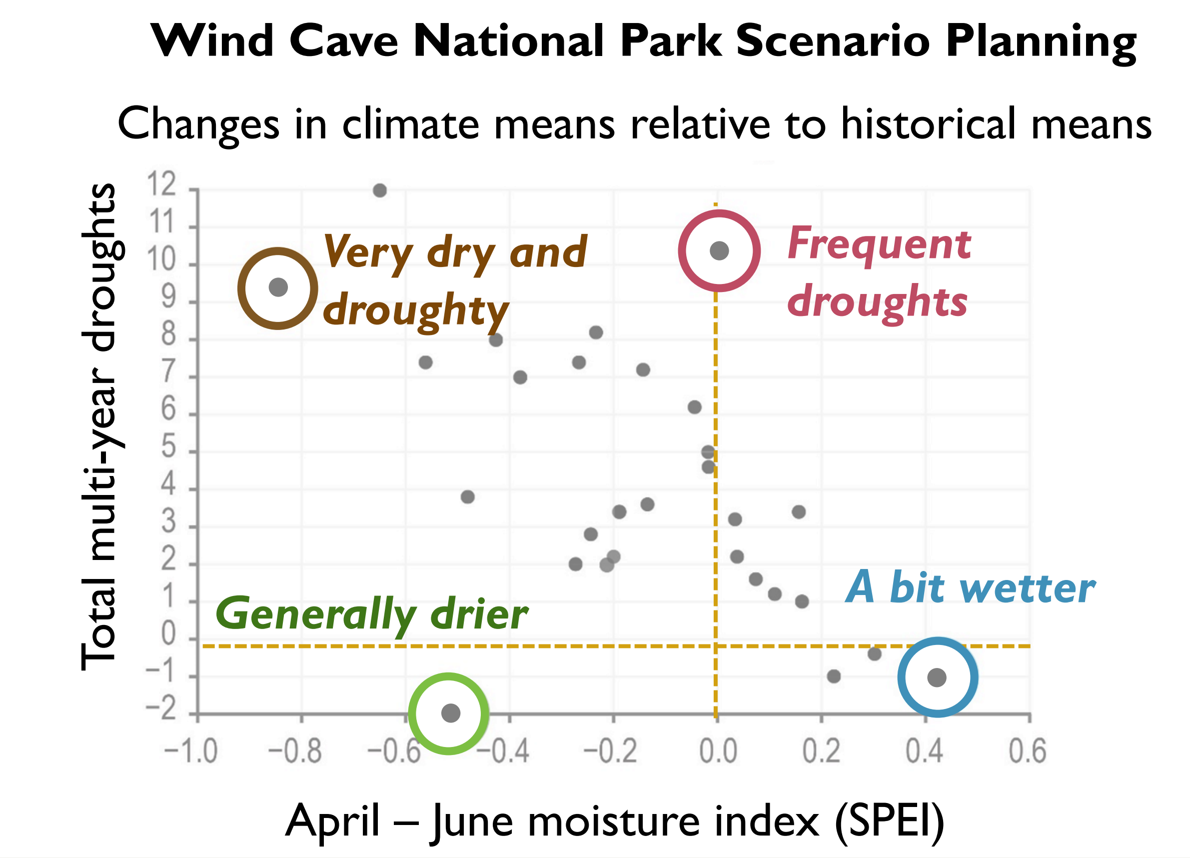
- *Relevant*
- *Divergent*
- *Plausible*
- *Challenging*

Adapted from NCA5

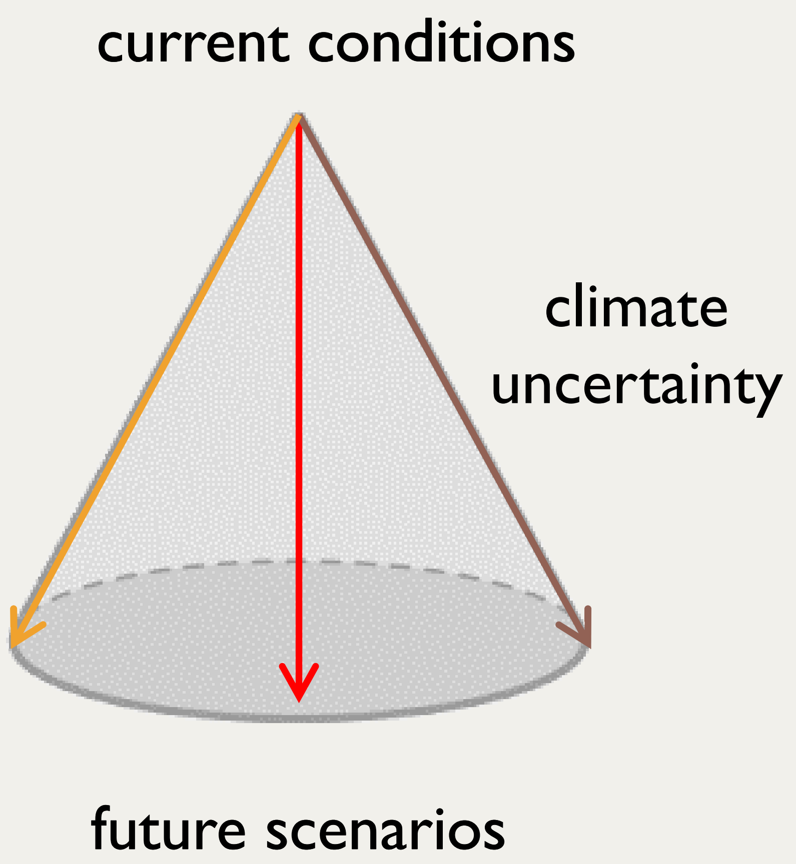
Ecological responses in scenario development: current state of practice

Climate futures

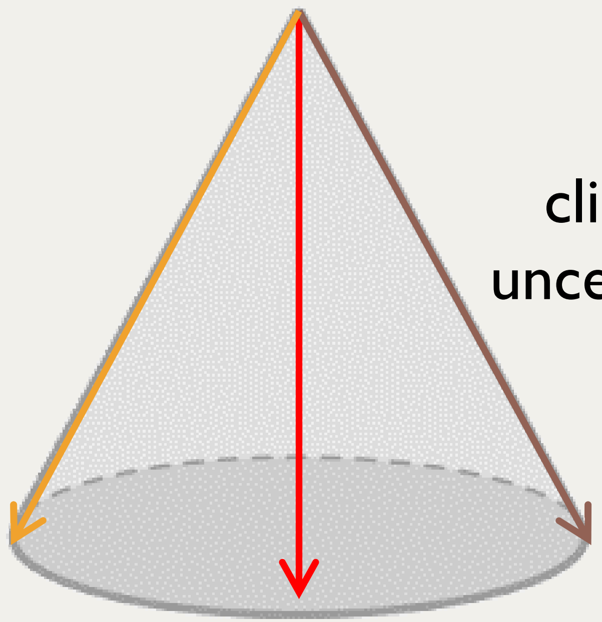
Ecological futures



What are we missing?



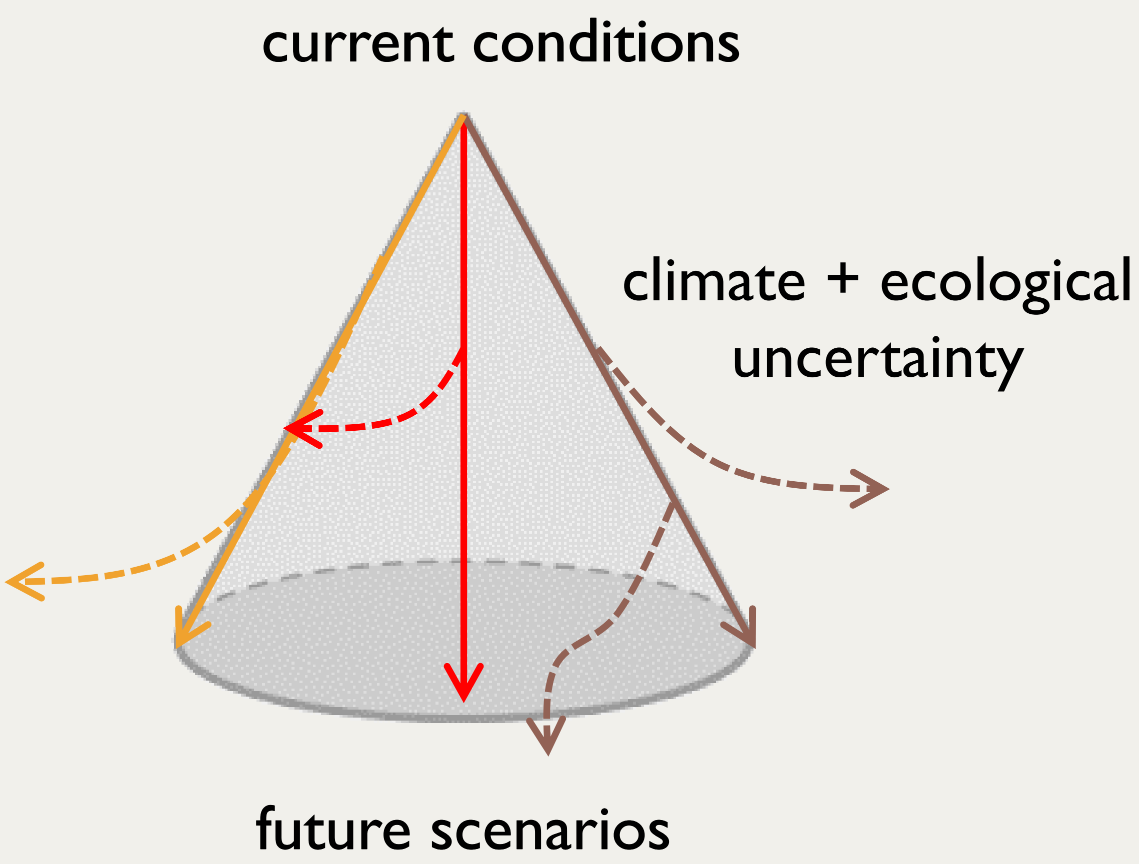
Graphic: W. Moss



What are we missing?

→ **Uncertainty in *ecological responses* to climate change**

Graphic: W. Moss



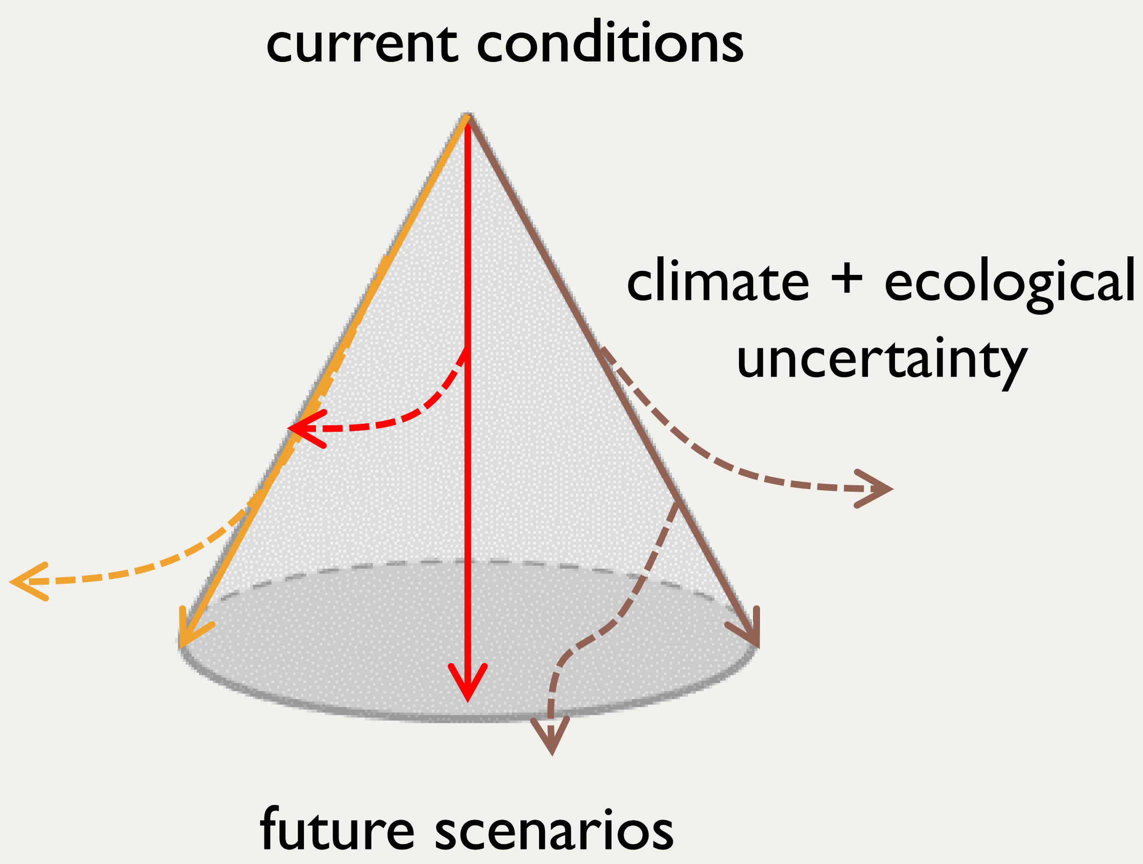
What are we missing?

→ **Uncertainty in *<u>ecological responses</u>* to climate change**

We can't reliably predict how an ecosystem will respond to a given change in climate!

Graphic: W. Moss

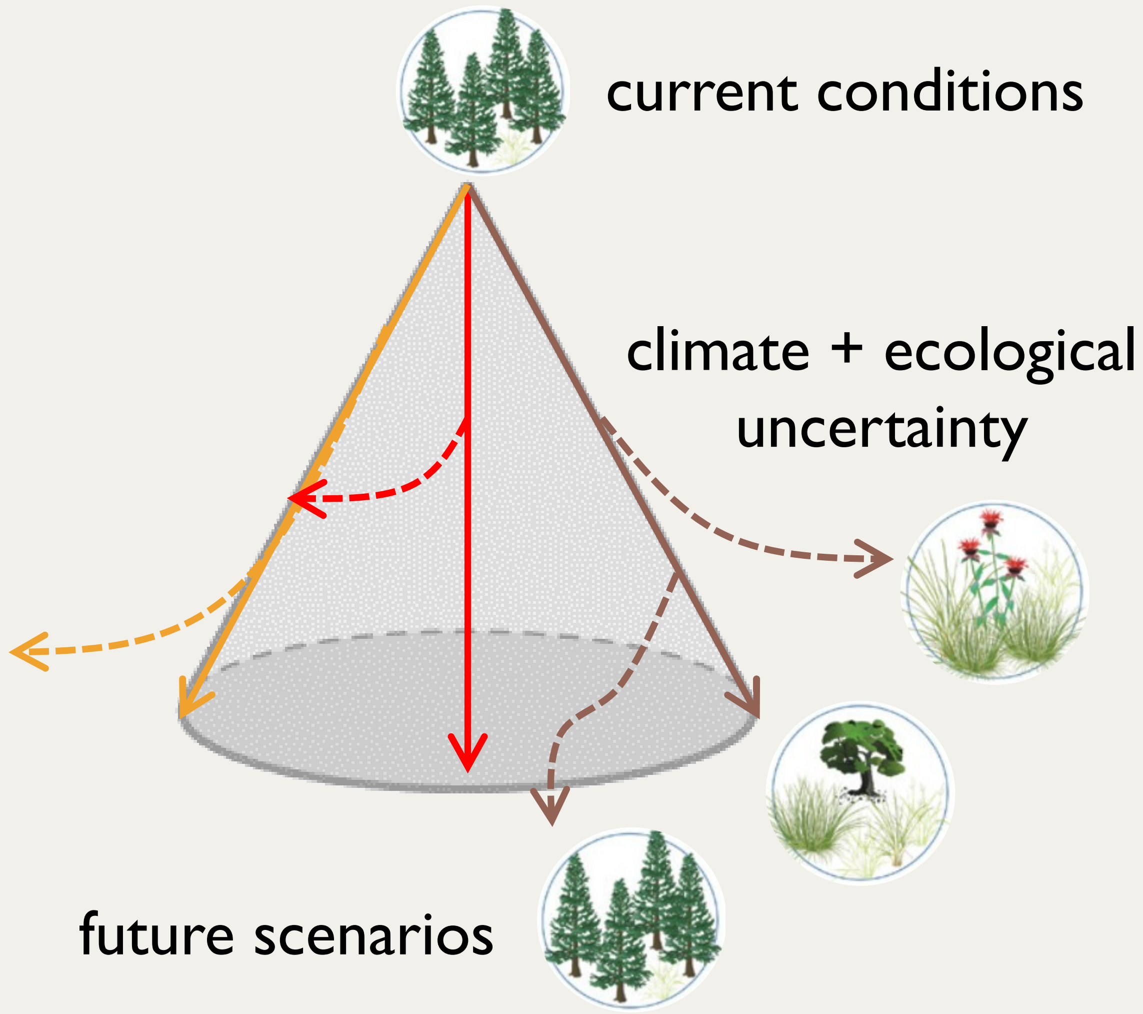
What limits our ability to predict ecological responses?



- Limited knowledge of climate-ecological relationships
- Interacting stressors
- Stochastic ecological dynamics
- Contingencies/context dependence
- No-analog conditions

Graphic: W. Moss

What limits our ability to predict ecological responses?



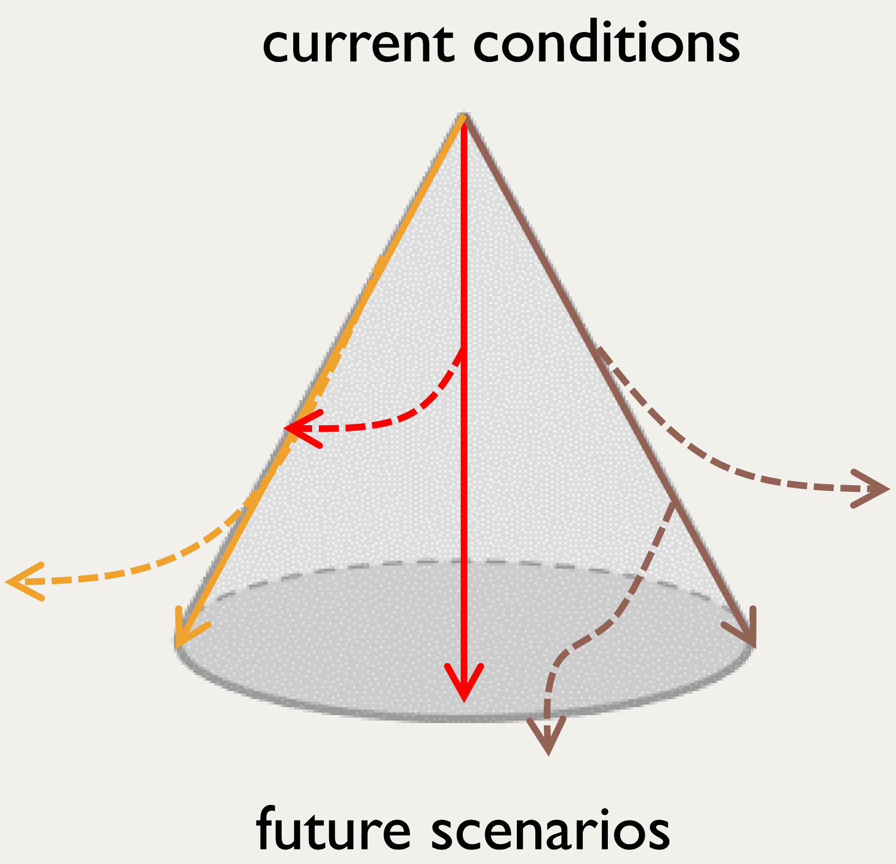
- Limited knowledge of climate-ecological relationships
- Interacting stressors
- Stochastic ecological dynamics
- Contingencies/context dependence
- No-analog conditions

Leads to…

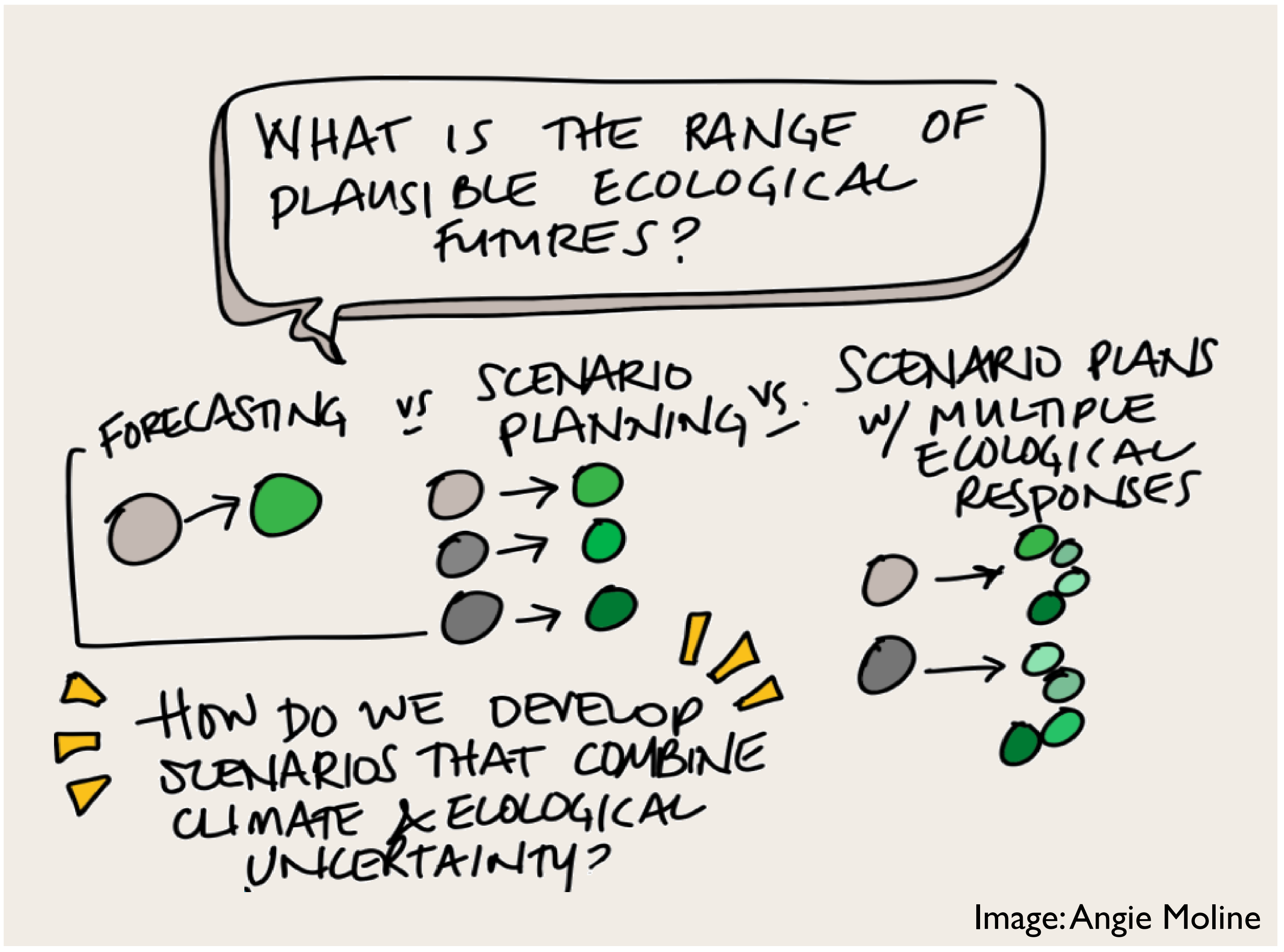
Multiple possible ecological outcomes under a given climate future

Crausbay et al. (2022) *BioScience;* Graphic: W. Moss

Towards improved ecological scenarios



Graphic: W. Moss



PART I

Ecological Transformation Working Group

Goal → use team science to develop a shared vision of approaches for crafting ecological scenarios

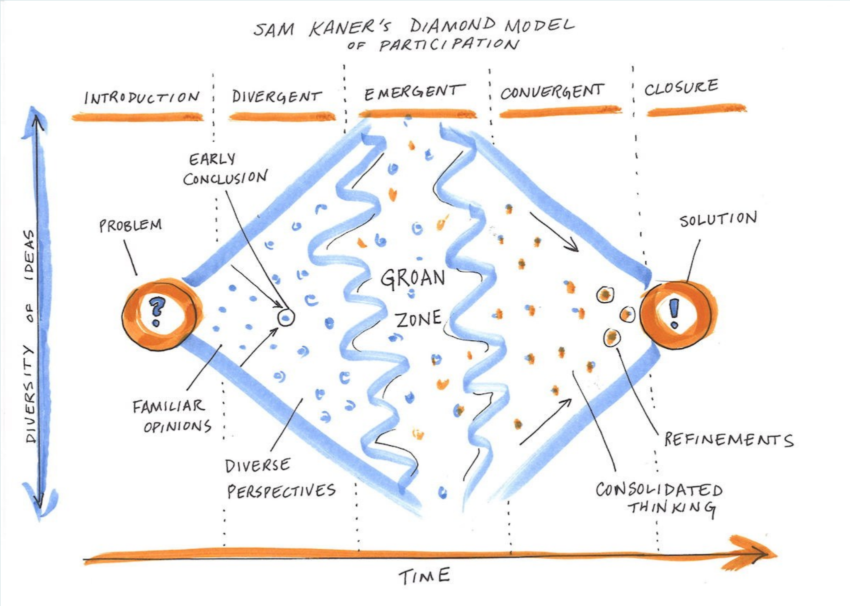


Image: Carrie Kappel

PART II

Ecological Scenarios Case Study (Nebraska Sandhills)

Goal → test out and refine the ecological scenarios approach through an applied case study

Juancarlos Giese, USFWS

ECOSCENARIOS WORKSHOP

July 17-18, 2023 ~ Boulder CO

Project team: Kyra Clark-Wolf (NC CASC), Wynne Moss (USGS), Imtiaz Rangwala (NC CASC), Helen Sofaer (USGS), Brian Miller (USGS)
Workshop participants: Orien Richmond (USFWS), Tyler Hoecker (NW CASC), Dawn Magness (USFWS), Jonathan Coop (Western Colorado Univ.), Joseph Barsugli (NOAA), Bill Travis (CU Boulder), Meagan Oldfather (USGS), Tony Ciocco (USGS), Amber Runyon (NPS), Jena Lewinsohn (USFWS), Robin Russell (USFWS), Nifer Wilkening (USFWS), Luca Palasti (CU Boulder)
Other working group members: Gregor Schuurman (NPS), Amy Symstad (USGS), Dominique Bachelet (OR State Univ), Renee Rondeau (CNHP), Shelley Crausbay (USFS)

“Key ingredients” for ecological scenarios

Exploring uncertainty in ecological dynamics

Characterizing trajectories of change

Looking “outside the box” to anticipate possible surprises

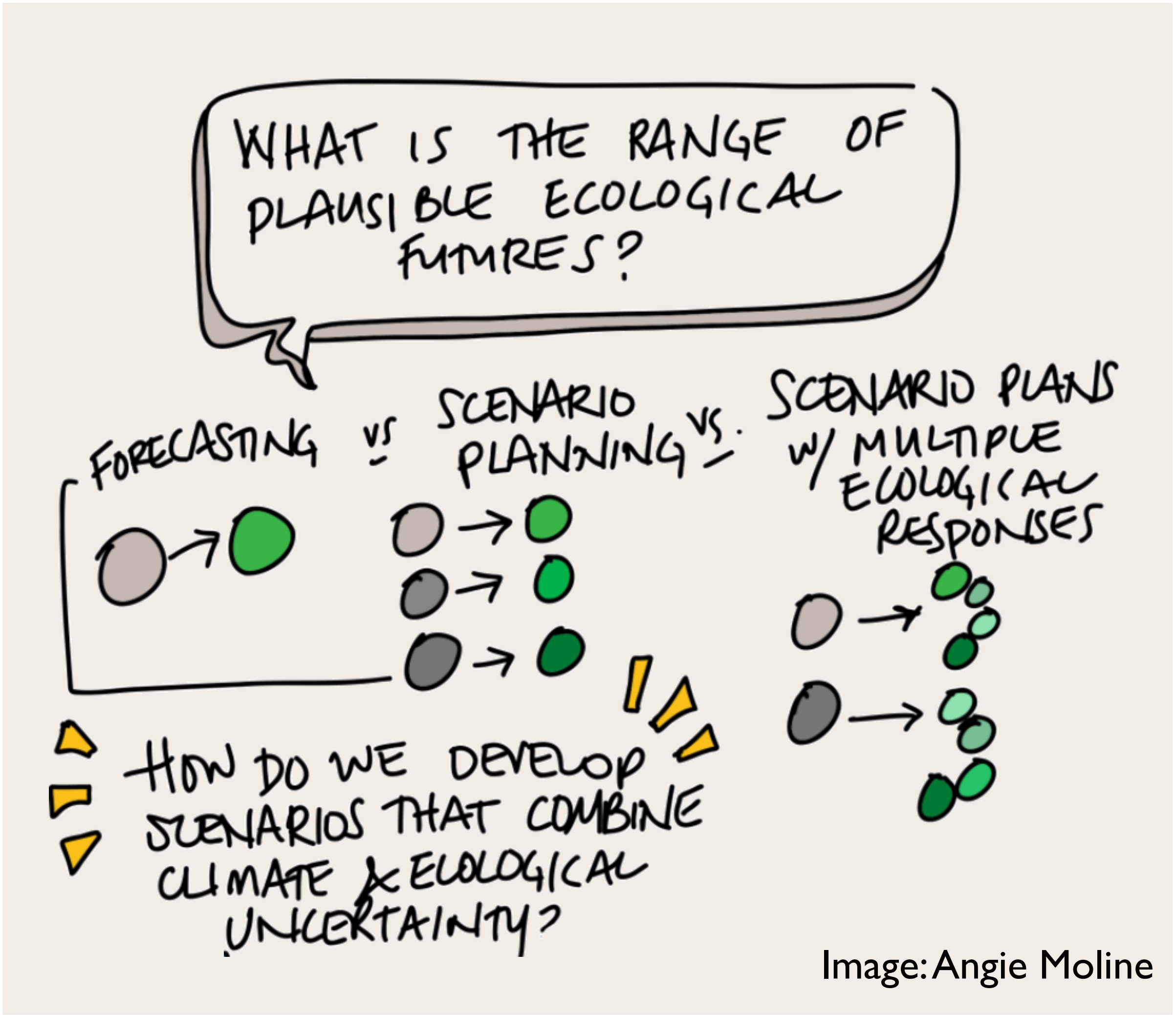


Image: Angie Moline

Clark-Wolf et al. 2025 *Ecosphere*

1. Exploring uncertainty in ecological dynamics

What are the most influential and uncertain sources of ecological divergence?

Ecological Drivers:

Biotic interactions

Feedbacks

Stochastic processes

Biogeography (e.g., dispersal & connectivity)

Ecological memory

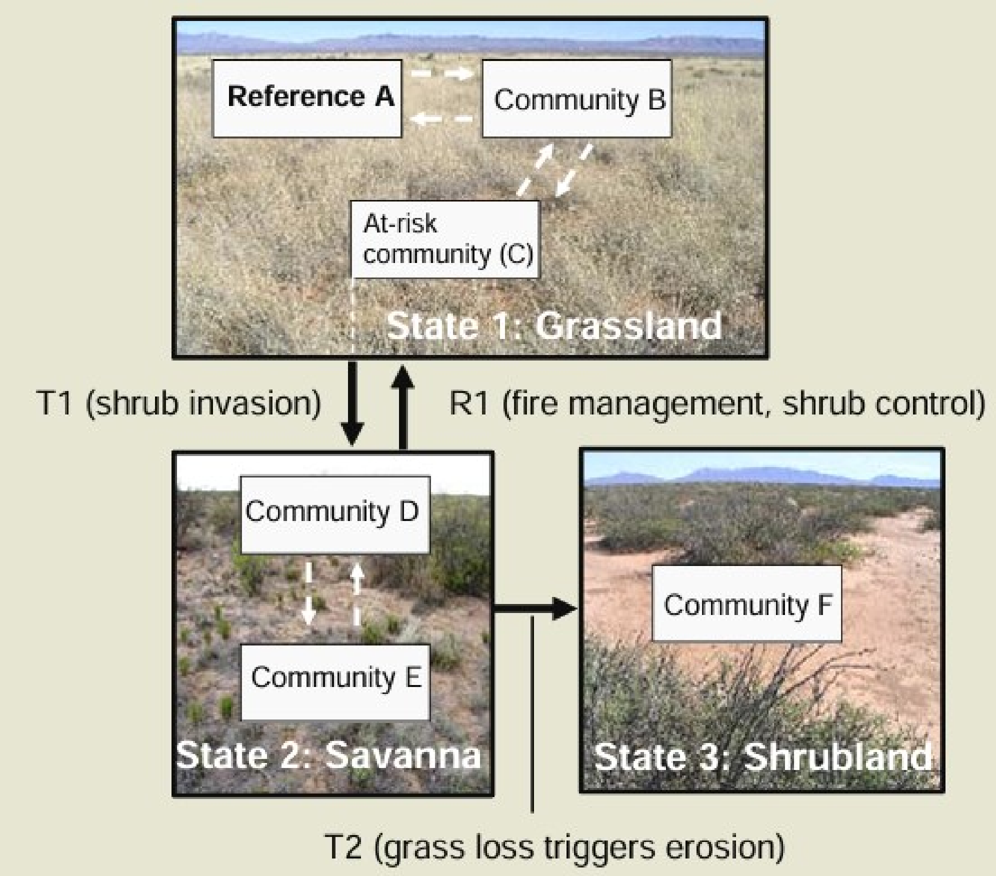
Lags

Physiological responses (CO_2, phenology, etc.)

Disturbance regime-change

Invasion

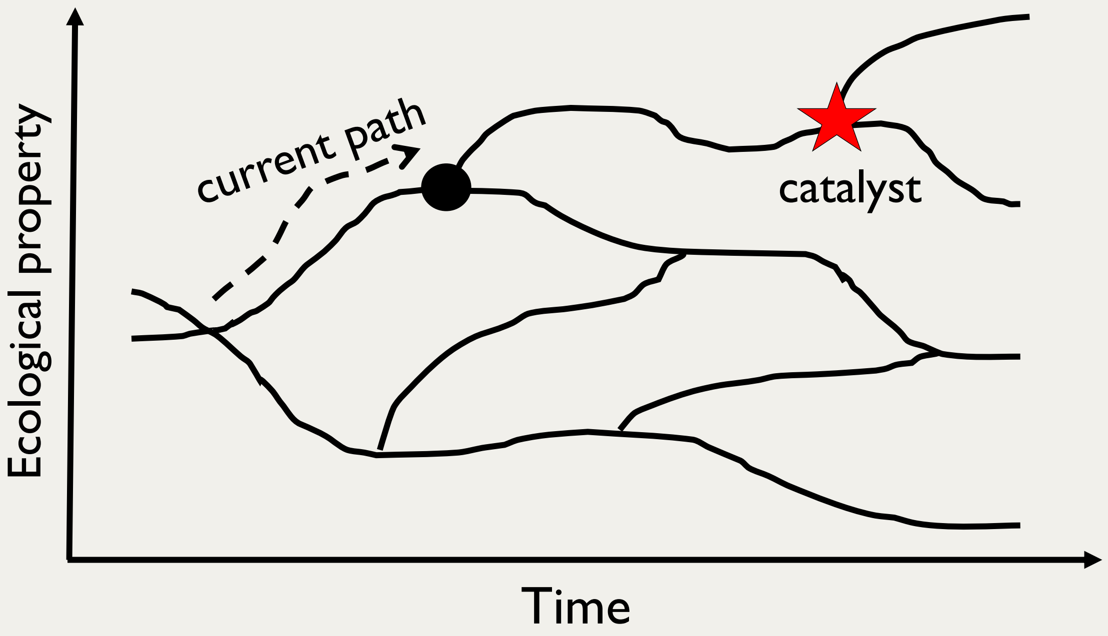
Climate sensitivities (including thresholds)

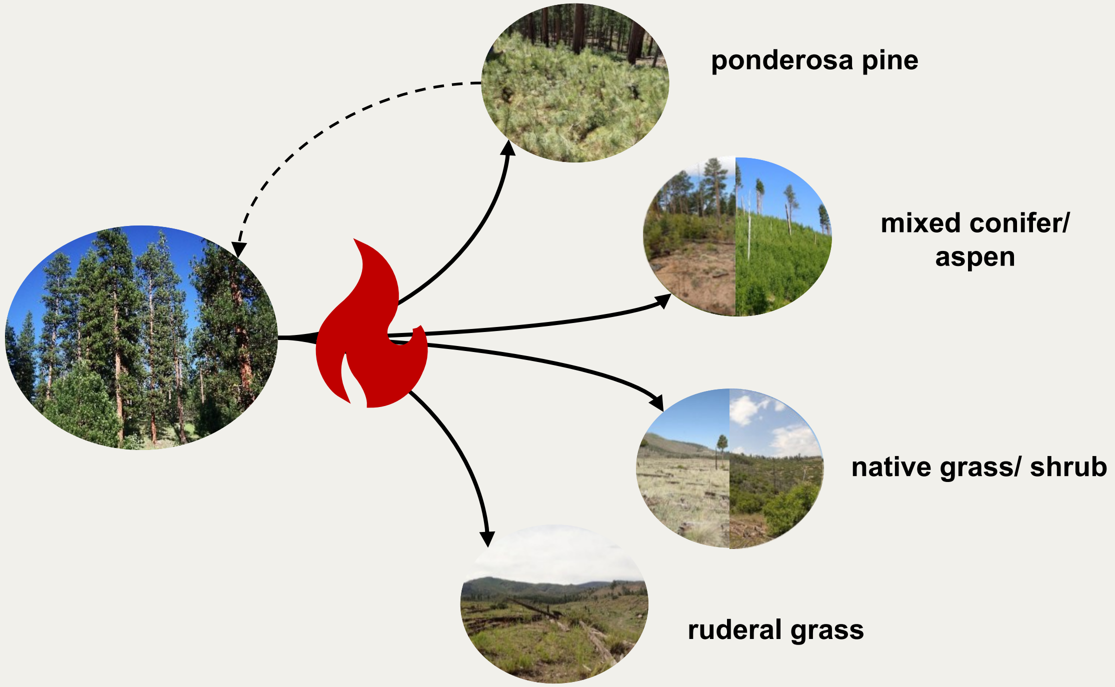


USDA/ Jornada Experimental Range

2. Thinking in trajectories

What are the mechanisms of transformation and the pathways through which ecological changes may unfold? What catalysts can shift the direction of change?



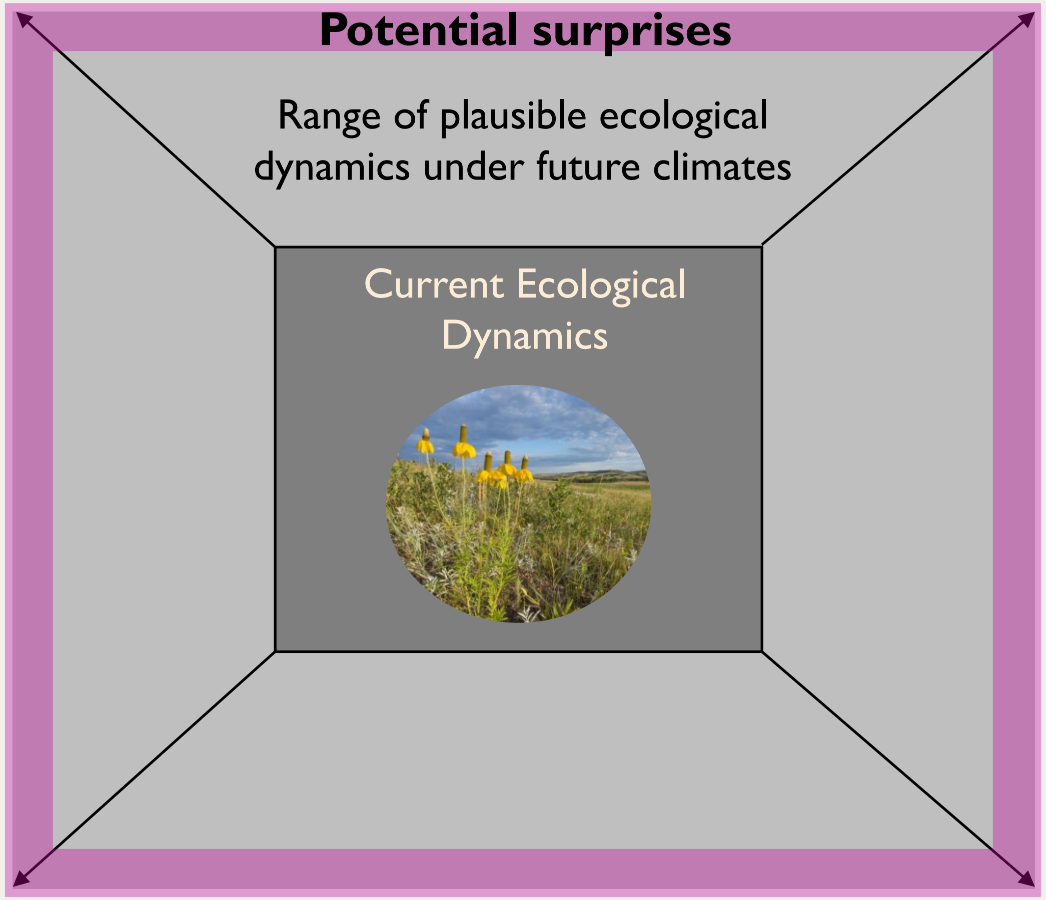


- Designing monitoring
- Identifying management levers

Adapted from Coop (2023) *Ecological Applications*

3. Exploring "out of the box" possibilities

What are the bounds of plausibility?
Are we comprehensively accounting for risk?



creative visioning

benchmarking to past extremes

"broadening the scope" of analogs in space and time

How can we implement these principles?

Exploring uncertainty in ecological dynamics

Characterizing trajectories of change

Looking "outside the box" to anticipate possible surprises

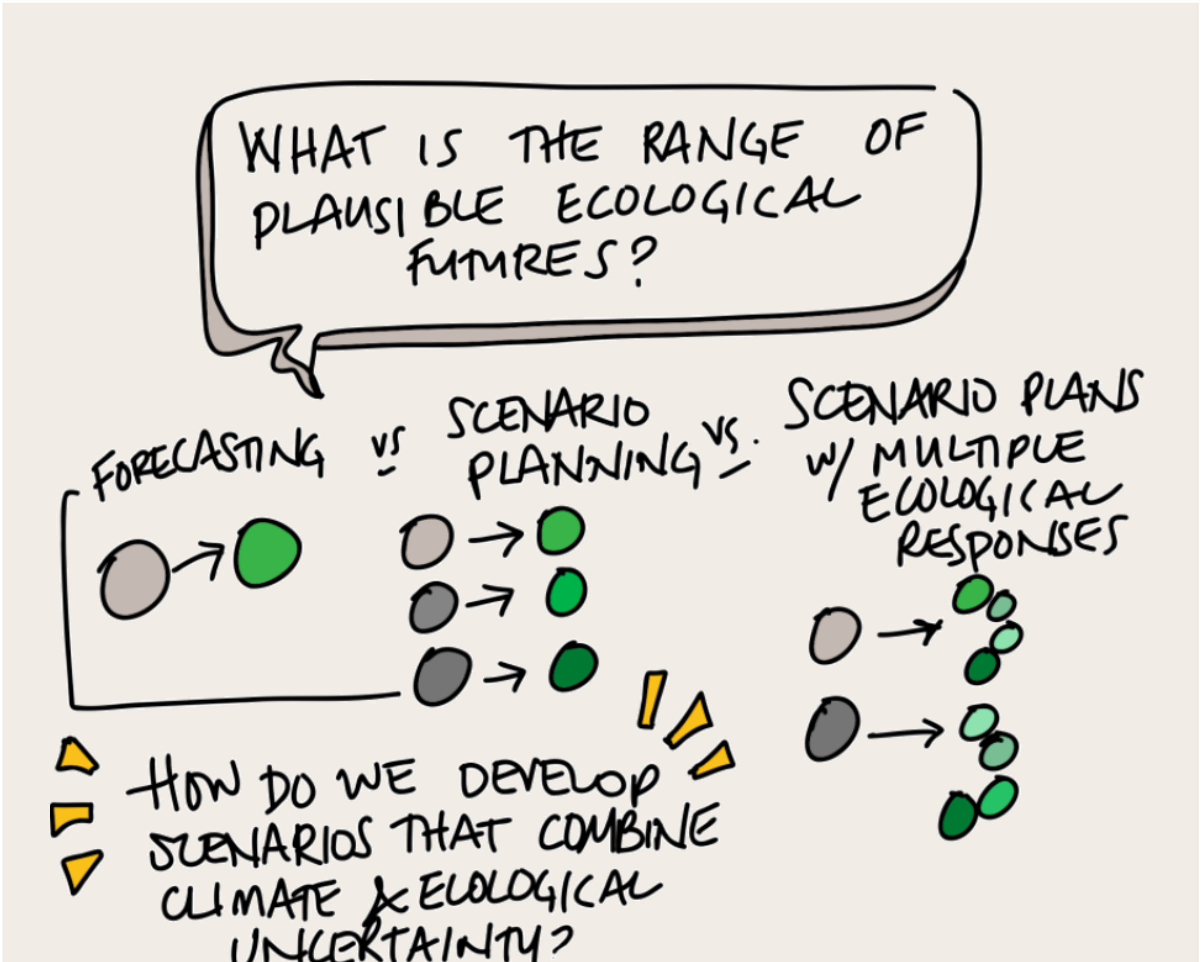
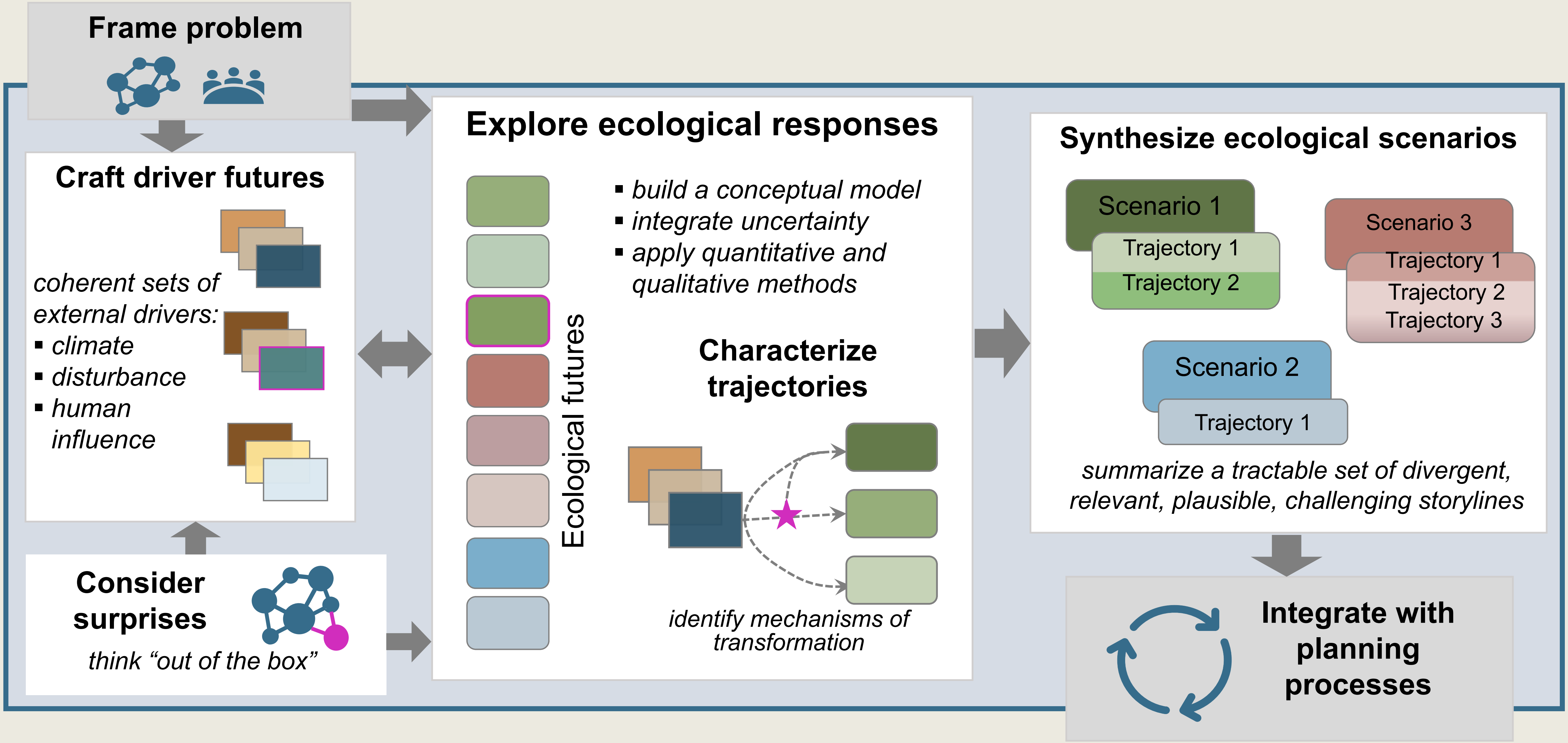


Image: Angie Moline

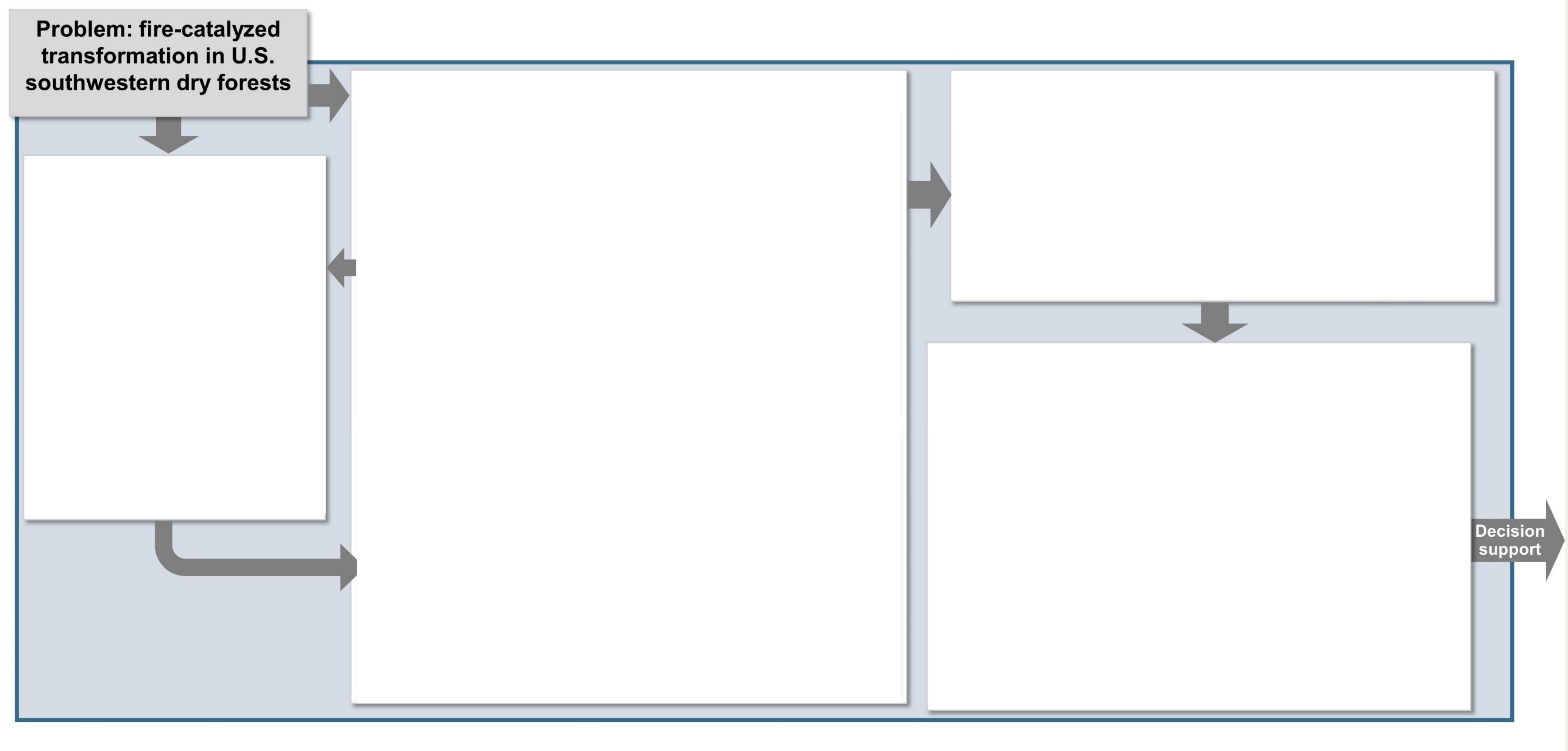
Clark-Wolf et al. 2025 *Ecosphere*

A general process for ecological scenario development



Clark-Wolf et al. 2025 *Ecosphere*

A case study for ecological scenario development



Clark-Wolf et al. 2025 *Ecosphere*, adapted from Coop 2023 *Ecol. Applications*

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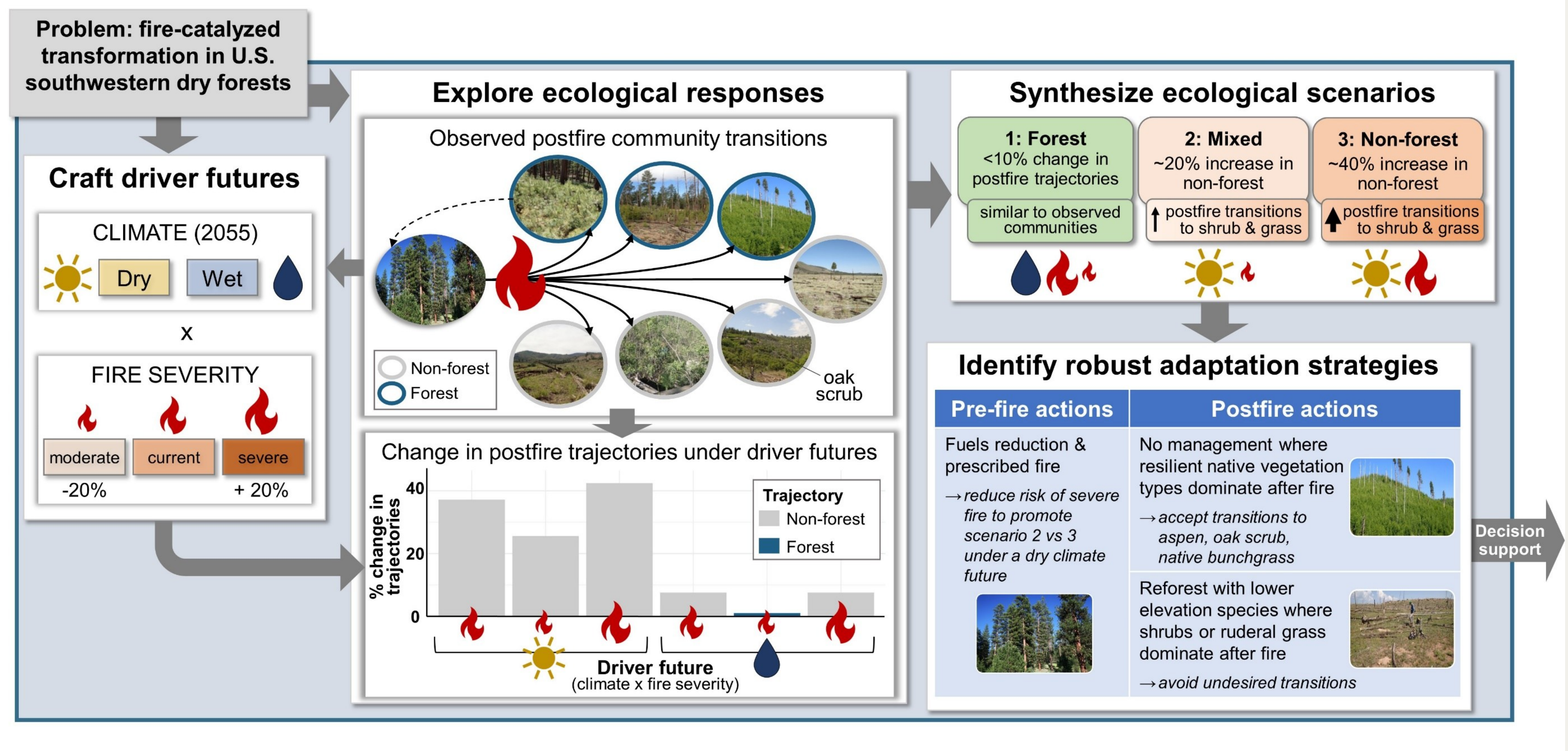
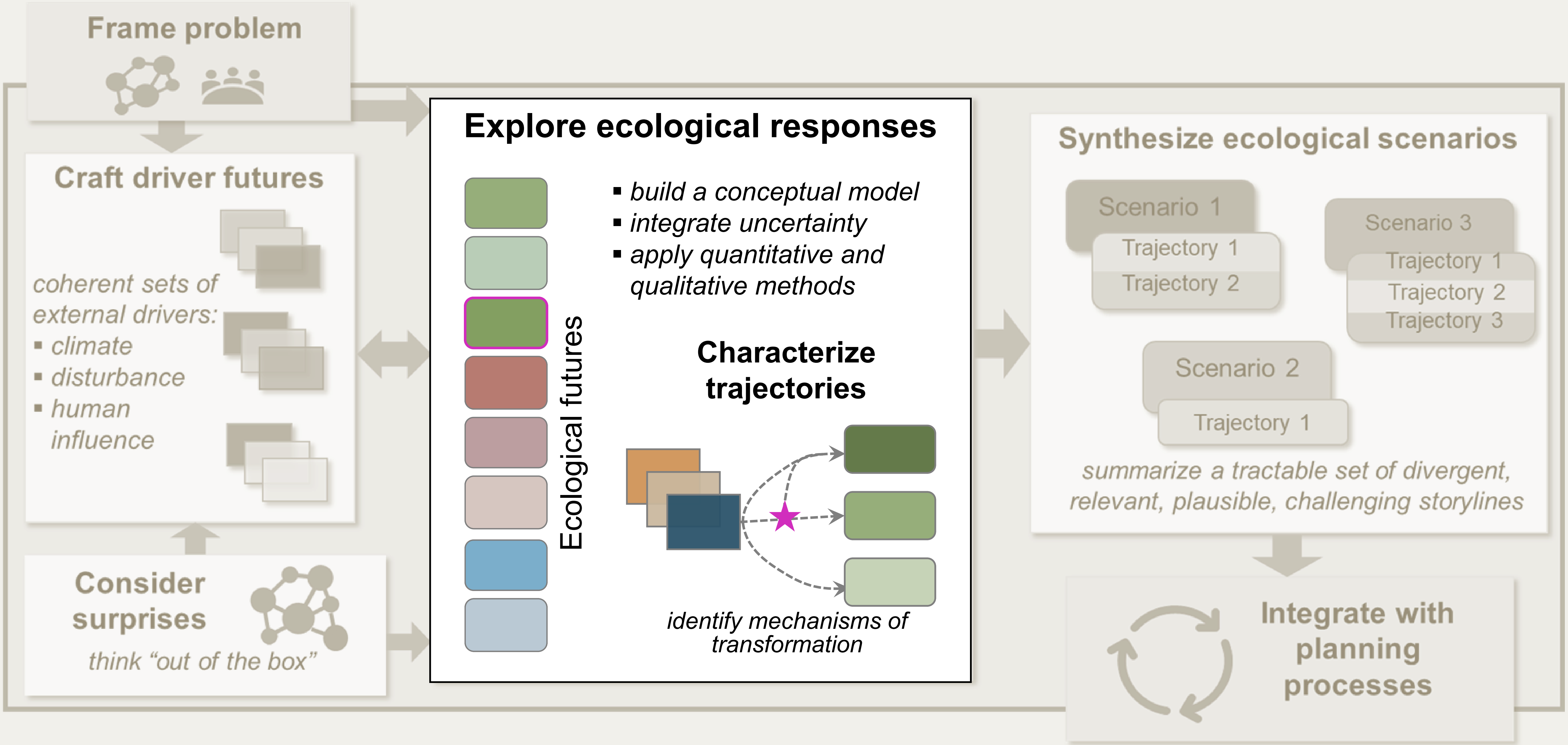


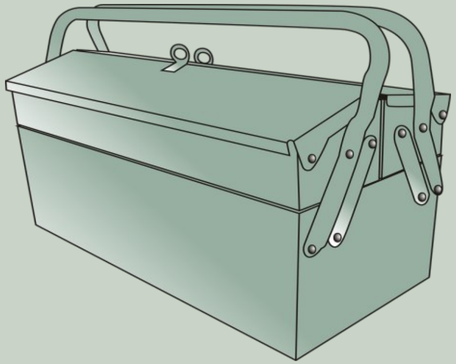
Clark-Wolf et al. 2025 *Ecosphere*, adapted from Coop 2023 *Ecol. Applications*

Methods for ecological scenario development



Clark-Wolf et al. 2025 *Ecosphere*

What are some ways to use existing tools to capture ecological uncertainties?



- Climate analogs
- Species distribution models
- Dynamic global vegetation models
- Population models
- Expert elicitation
- And more!

There is no silver bullet when it comes to ecological modeling

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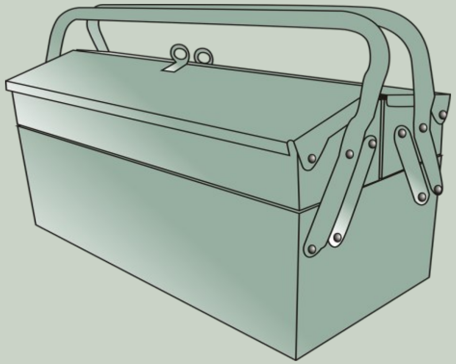

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Clark-Wolf et al. 2025 *Ecosphere*

Tools to explore ecological responses

Model for divergence: draw on the full range of modeling results or quantiles of prediction intervals rather than seeking a central tendency or convergent endpoint

Sensitivity analyses: explore consequences of parameter values to identify important ecological uncertainties

Stochastic models*: use models that can represent stochastic processes and dynamics (e.g., simulation or population models)

Time series methods*: identify plausible ecological responses based on past dynamics using time series data or paleo records

Space-for-time methods: identify plausible ecological states using geographic analogs, climate envelope models, or similar

Event-driven approaches*: test ecological responses to climate extremes or other major disturbances (e.g., fire, insects)

Multi-method approaches: draw on multiple types of information and/or models to develop ecological scenarios

Close calls*: identify plausible transformations based on past events with strong population or community responses

Participatory scenario development: explore ecological implications of driver futures in a workshop process

includes **creative visioning:** consider new feedbacks, nonlinearities, compound events, invasions or species interactions that could lead to surprises

Reverse engineering*: work backward from plausible future ecological states to describe how changes could unfold

= quantitative = qualitative

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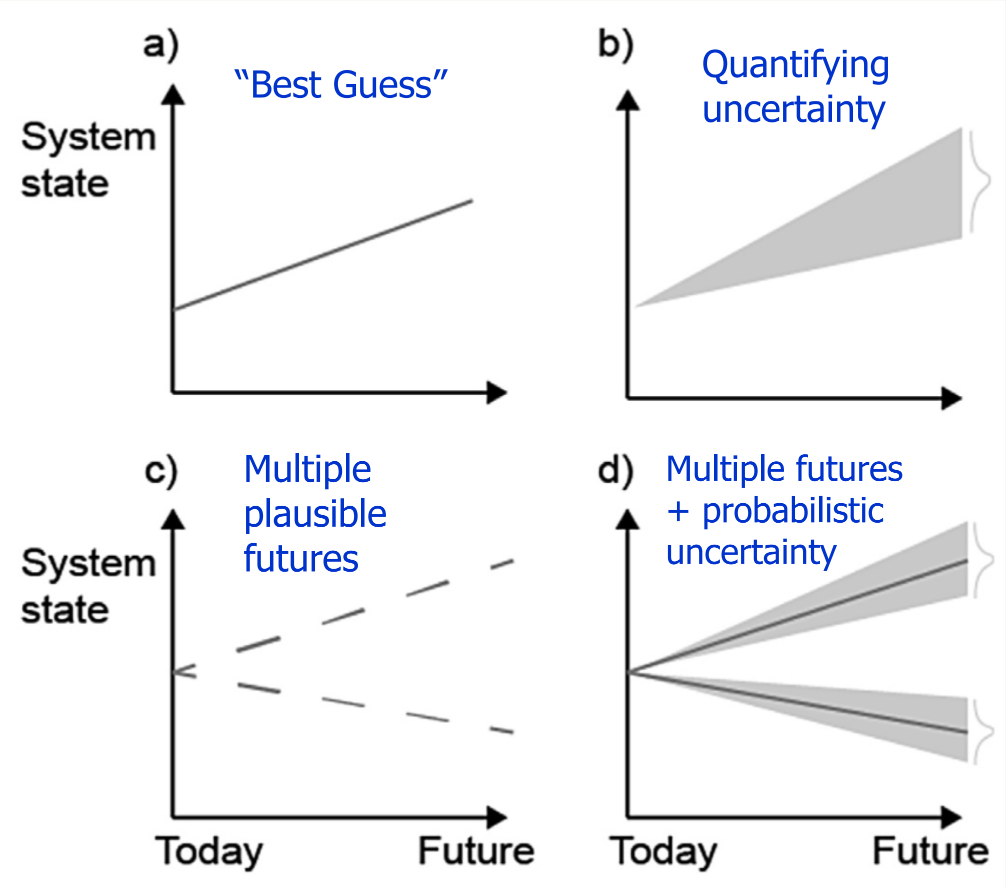

Ecologists can provide more actionable science by considering multiple futures

Clark-Wolf et al. 2025 *Ecosphere*

Maier et al. 2016 *Environmental Modelling and Software*

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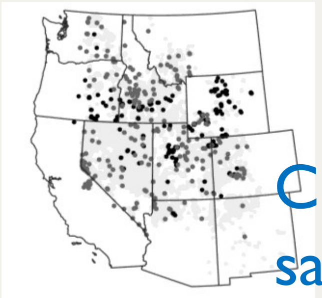
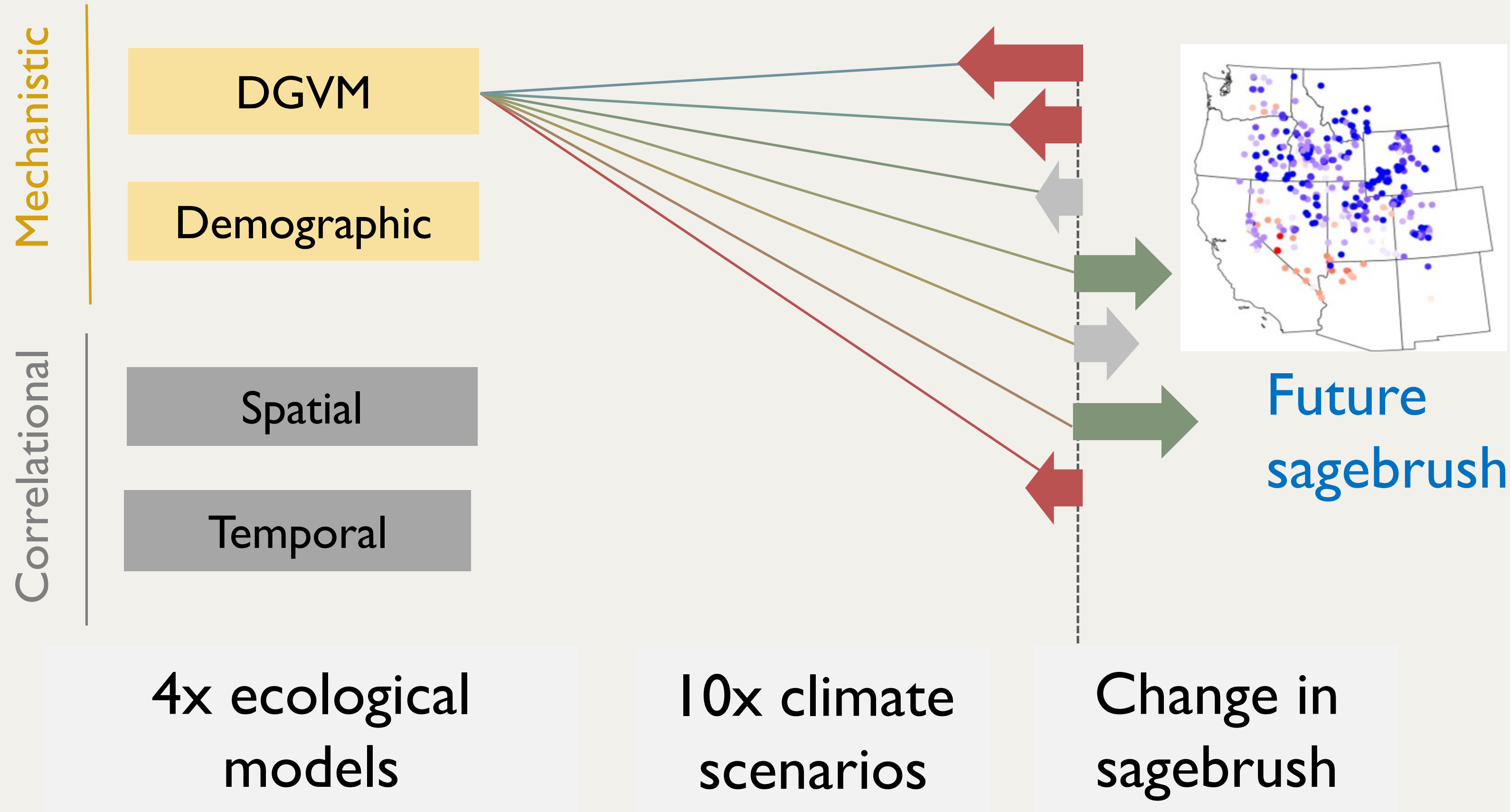


Current sagebrush

Different modeling frameworks reveal ecological divergence



Clark-Wolf et al. 2025 *Ecosphere*

Graphic: W. Moss

Renwick et al. 2018 *Global Change Biology*

Tools to explore ecological responses

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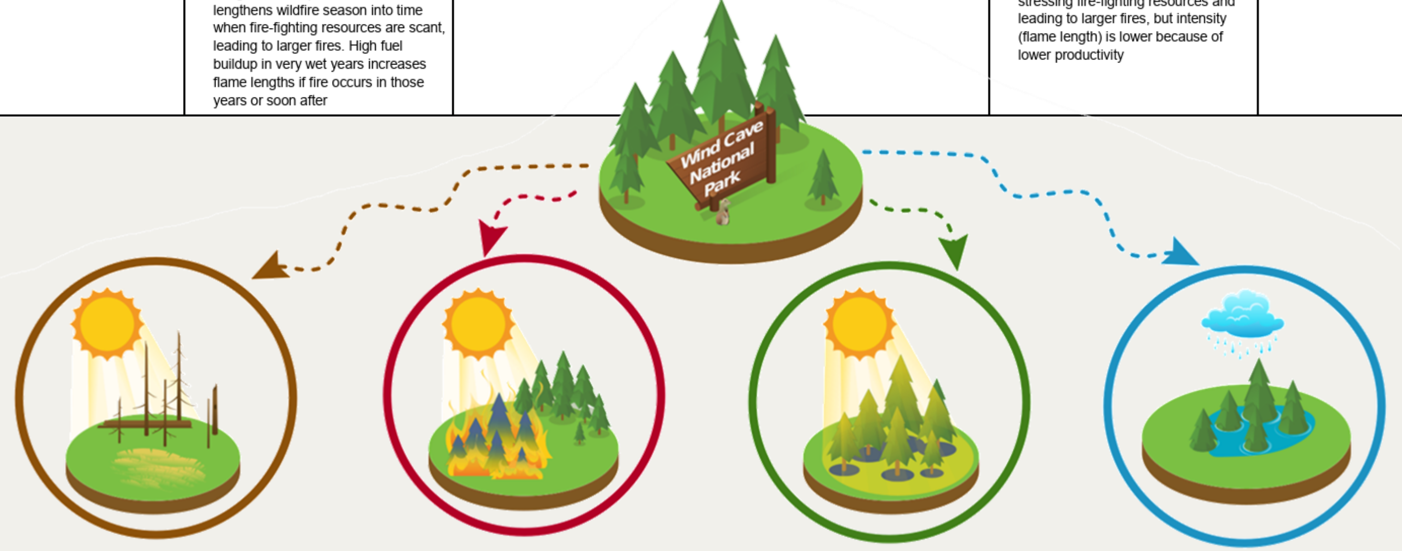
Clark-Wolf et al. 2025
Ecosphere

Table 6 (continued). Scenario planning workgroup-envisioned developments and resource implications (vulnerabilities) for WICA climate futures for each priority resource and resource component. Bold text signifies "red flag" events, i.e., impactful outcomes unique to a single scenario (NPS 2020). All references to shifts refer to status under historical conditions. Table A6-6 is a more accessible version of this same table that is designed specifically to be easier to read by screen reading software for people with certain visual and cognitive impairments; or with low vision, various types of color-blindness, or cannot read the text against some of the table cell background colors used.

Priority	Resource component	Log Ride	Hourglass	Jenga	Convection Oven	Common across all/most scenarios
Vegetation	Prairie	• Exotic species: Much warmer winters allow establishment of new exotics (some potentially invasive) • Perennial exotic cool-season grasses (Kentucky bluegrass and smooth brome) and Canada thistle experience boom years but suffering in drought years may balance out to no trend • Exotic species: Moisture-loving annuals/ biennials (sweetclover, mullein, annual bromes -- annual bromes especially benefit from greater proportion of precip in winter) boom in wet years but persist in seed bank through dry years to create overall increasing trend • Productivity: Drought indices indicate that productivity will usually be somewhat lower, but occasional very wet years punctuate this trend with some very-high-productivity years that favor cool-season grasses • Prescribed fire: Very wet years have limited prescribed fire opportunities in spring and possibly fall, but burns can still be accomplished in other years. Much earlier spring green-up means timing of burns would have to be earlier. Much warmer winters allow more prescribed fire in winter, but higher summer-fall fire danger reduces opportunities for fall prescribed fire • Wildfire: Higher summer-fall fire danger overall, plus warmer winters, lengthens wildfire season into time when fire-fighting resources are scant, leading to larger fires. High fuel buildup in very wet years increases flame lengths if fire occurs in those years or soon after	• Exotic species: Little change or decreasing trend in current problem exotics, which tend to do well with higher (especially spring) moisture. Conditions neither more nor less favorable for new exotics • Productivity: Consistently lower productivity; warm-season grasses decline less than cool-season grasses due to large decrease in early growing season moisture availability but only moderate summer-fall PET increase • Prescribed fire: Lower spring moisture increases opportunities for spring prescribed fire, with season starting moderately earlier than now and some more opportunities in winter. Moderately higher summer-fall fire danger moderately decreases opportunities for prescribed fire in fall • Wildfire: A slight increase in fire risk and length of fire season (increased summer-fall PET) is accompanied by lower intensity (shorter flame lengths) due to consistently lower productivity	• Exotic species: Reduced vigor of many perennial species, creating opportunities for short-lived, drought-tolerant weeds like Russian thistle and kochia, as well as drought-tolerant perennials like white horehound and others not yet in the park (i.e., from further south or west) • Productivity: First half of future-period (2025-2040) productivity may be similar to historical productivity, but productivity in second half of future period (2040-2055) drops sharply due to sharply increased temperatures and some very dry years. Warm-season grasses decline more than cool-season grasses • Prescribed fire: Shifted prescribed fire opportunities to winter (December-March) • Wildfire: Much warmer winters and higher summer-fall PET increase fire risk, length of fire season, and size of fires in the second half of the future period, but fire intensity (flame length) is lower because of less fuel	• Exotic species: Most of the current problem exotics (cool-season perennial grasses, mullein, sweetclover, Canada thistle) decline but annual bromes and other exotic annual grasses not yet in the park increase. Horehound and other (some new) drought-tolerant exotics increase • Productivity: Overall grass production, both warm- and cool-season, decreases by up to 50%. Deeply rooted shrubs such as rabbit brush and sagebrush (if they migrate to the park), as well as drought tolerant succulents, benefit from less grass competition and the shift to higher percentage of precipitation falling in winter. They still remain a minor component of the ecosystem because the winter precip shift is moderate • All grasses decline – including Kentucky bluegrass. • Cheatgrass thrives due to increased winter precipitation • Prescribed fire: Reduced fuel build-up from lower overall production, combined with reduced vigor of exotic cool-season grasses, reduces the ability and desire to conduct fires as frequently as is now desired • Wildfire: More frequent, fire season extends through much of the year, stressing fire-fighting resources and leading to larger fires, but intensity (flame length) is lower because of lower productivity	• Exotic species: Opportunities for new exotics to establish (3 of 4 scenarios) • Productivity: Lower productivity • Prescribed fire: Shifted timing for prescribed fires, or less opportunity • Wildfire: Increased fire risk and fire season length



Runyon et al. 2021

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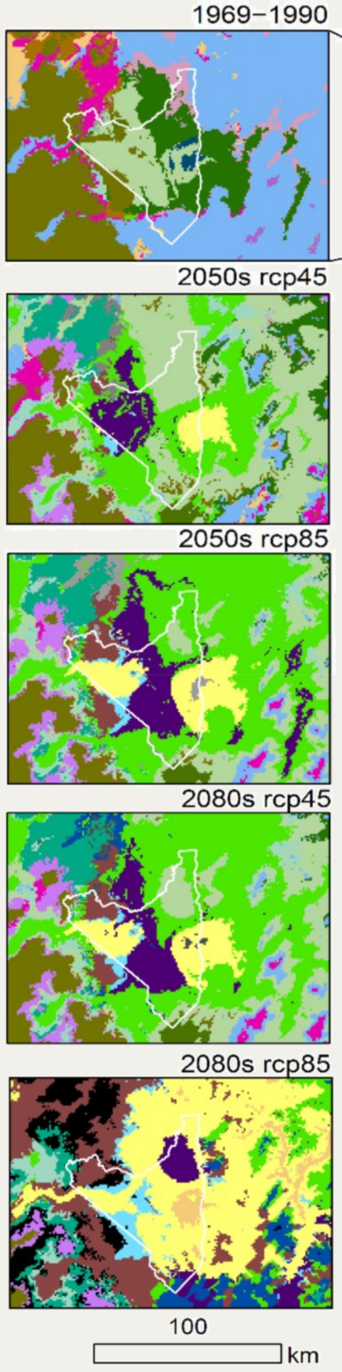
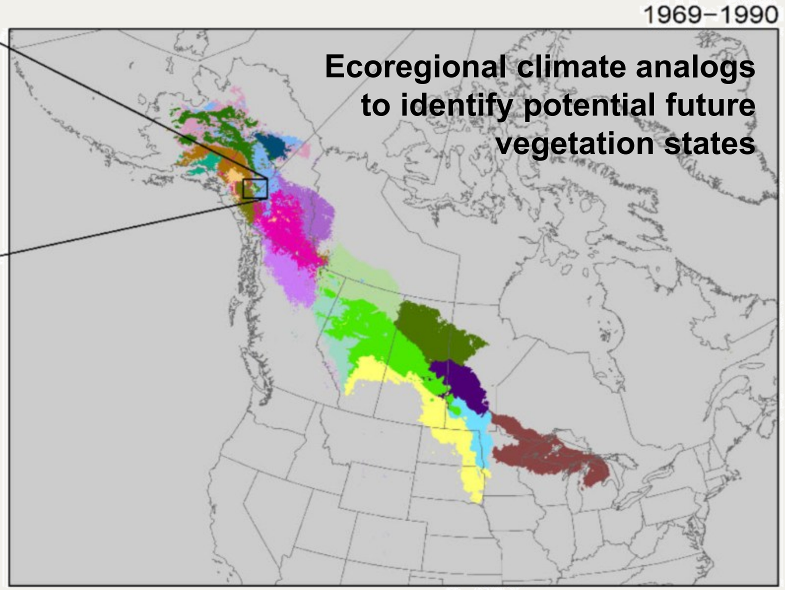
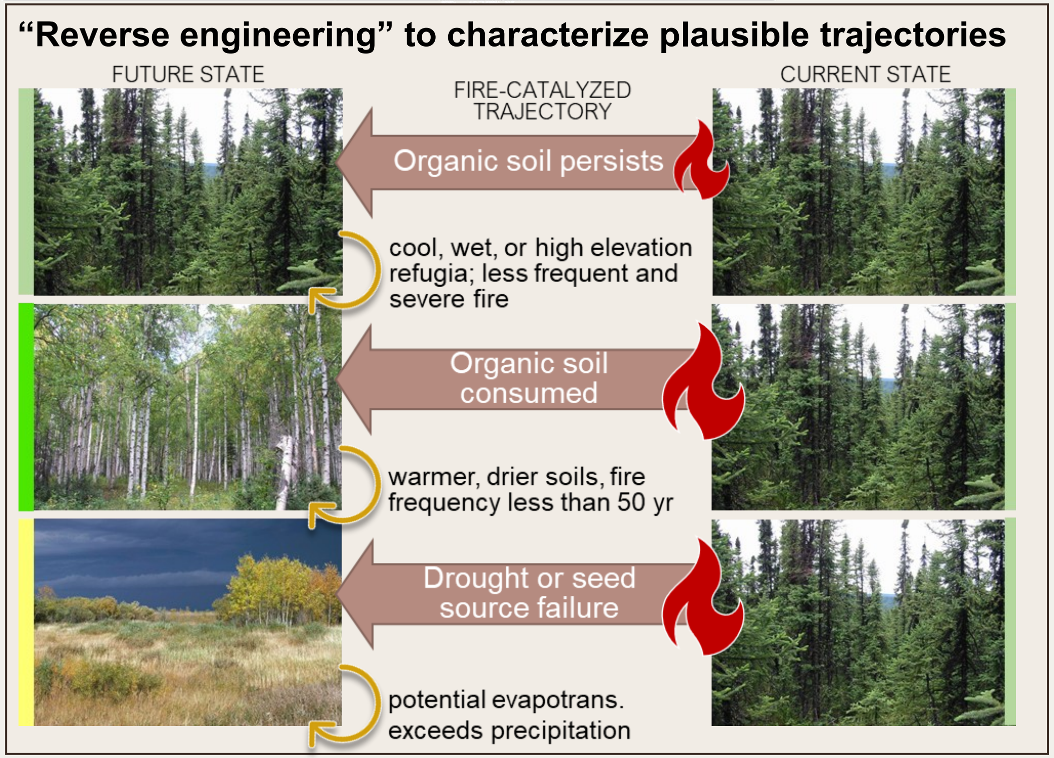






Clark-Wolf et al. 2025 *Ecosphere*

Magness et al. 2022 *Earth*

Putting it all together

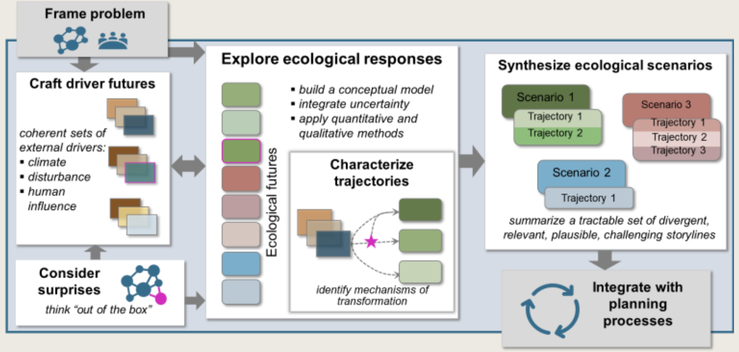
Set of Principles

Exploring uncertainty in ecological dynamics

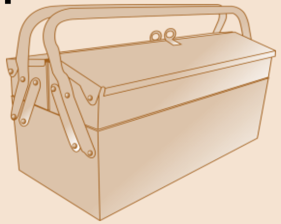
Characterizing trajectories of change

Looking "outside the box" to anticipate possible surprises

General Process



Suite of Tools



Tools to explore ecological responses

- **Model for divergence:** draw on the full range of modeling results or quantiles of prediction intervals rather than seeking a central tendency or convergent endpoint
- **Sensitivity analyses:** explore consequences of parameter values to identify important ecological uncertainties
- **Stochastic models*:** use models that can represent stochastic processes and dynamics (e.g., simulation or population models)
- **Time series methods*:** identify plausible ecological responses based on past dynamics using time series data or paleo records
- **Space-for-time methods:** identify plausible ecological states using geographic analogs, climate envelope models, or similar
- **Event-driven approaches*:** test ecological responses to climate extremes or other major disturbances (e.g., fire, insects)
- **Multi-method approaches:** draw on multiple types of information and/or models to develop ecological scenarios
- **Close calls*:** identify plausible transformations based on past events with strong population or community responses
- **Participatory scenario development:** explore ecological implications of driver futures in a workshop process
  - *includes* **creative visioning:** consider new feedbacks, nonlinearities, compound events, invasions or species interactions that could lead to surprises
- **Reverse engineering***: work backward from plausible future ecological states to describe how changes could unfold

⊞ = quantitative   (head icon) = qualitative

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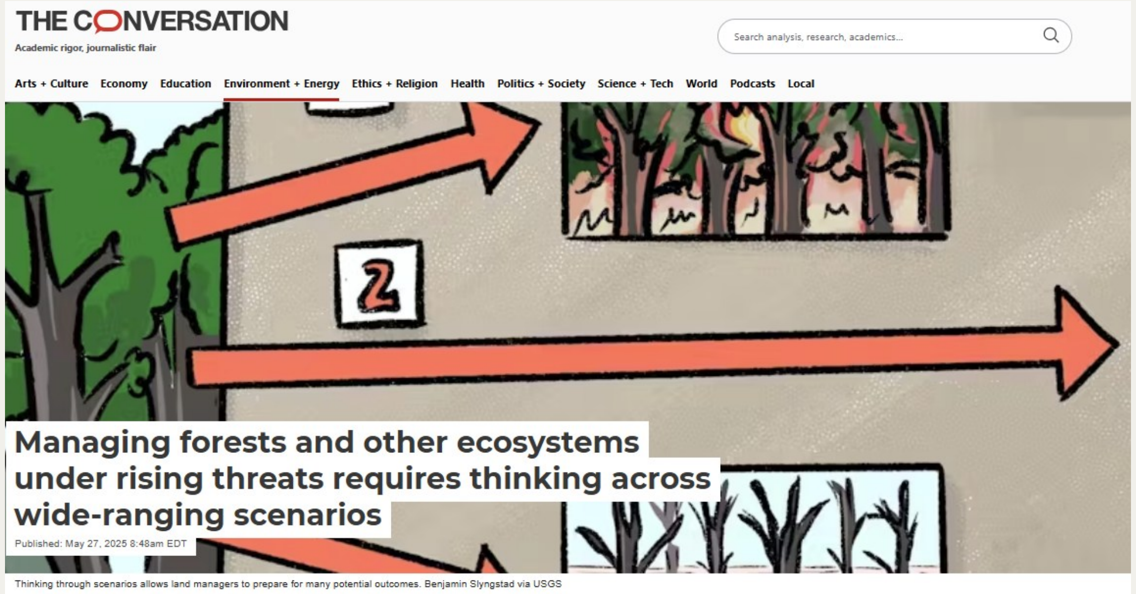
Ecological scenarios: Embracing ecological uncertainty in an era of global change

K. Clark-Wolf, W. E. Moss, B. W. Miller, I. Rangwala, H. R. Sofaer, G. W. Schuurman, D. Magness, A. J. Symstad, J. D. Coop, D. B. Bachelet, J. J. Barsugli, A. Ciocco, S. D. Crausbay ... See all authors

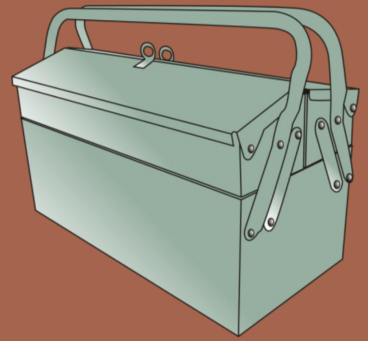
First published: 24 May 2025 | https://doi.org/10.1002/ecs2.70278

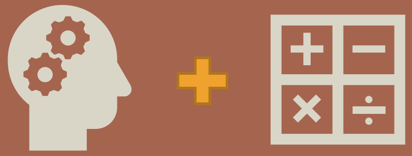


Thinking through scenarios allows land managers to prepare for many potential outcomes. Benjamin Slyngstad via USGS

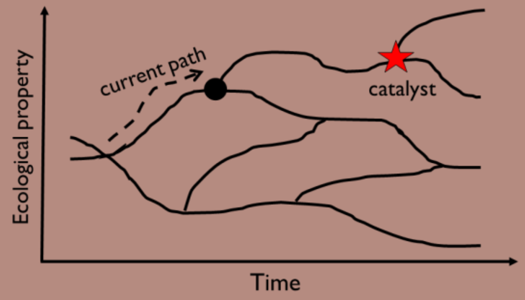
What's Next?

Building the toolbox

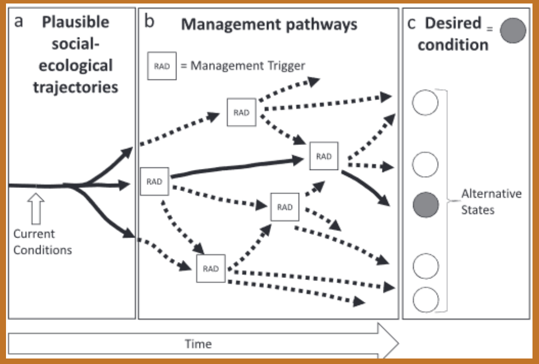




Research



Practice



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"Test driving" our approach

PART I

Ecological Transformation Working Group

Goal → use team science to develop a shared vision of approaches for crafting ecological scenarios

PART II

Ecological Scenarios Case Study (Nebraska Sand Hills)

Goal → test out and refine the ecological scenarios approach through an applied case study

ECOSCENARIOS WORKSHOP

July 17-18, 2023 ~ Boulder CO

moline CREATIVE

SANDHILLS

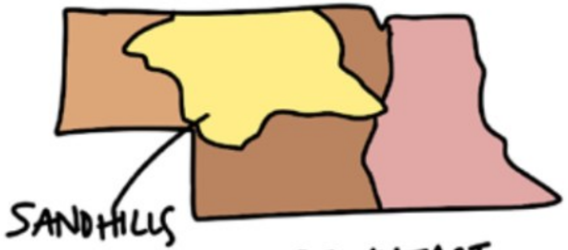
CASE STUDY

MIXED GRASS PRAIRIE

BIRD HABITAT

UNCERTAINTY...

- PRECIP & WATER AVAILABILITY?
- CO_2 ENRICHMENT
- CLIMATE & INVASIVE SPP. + FIRE
- PRIVATE LAND USE



* LARGEST INTACT NATIVE GRASSLAND (≈98% PRIVATE OWNED) IN N. AMERICA

FUTURE

- COULD STAY GRASS... (supports birds that need grass)
- COULD BE MOBILE SAND DUNES...
- COULD BECOME WOODLAND...

ARE THERE REFUGIA?

IF SO → HOW WOULD YOU MANAGE?

- DISTURBANCE REGIME △
  - FIRE, GRAZERS
- CLIMATE
  - HOTTER.
  - WETTER? MAYBE

Visual notes of the Sand Hills case study presentation

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STREAMSIDE RESTORATION AREA PLEASE KEEP OUT
Stay on Trail

Setting the project scope

What features of Sandhills wetlands and grasslands do you manage for?

Please identify/add resources that are most relevant to your management objectives, as well as those that might be particularly sensitive to climate change (feel free to add comments as well)

[drag and drop a check mark to indicate which resources are most important]

Grassland resources & functions:

Initial candidates	**Relative cover: grass, forb, woody**	**Native plant diversity**	**Forage production (not a focus on refuges)**	**Grassland structure (height, density, litter, bare ground)**
Other potential metrics	Invasive plant species; are new species showing up, or is there a change in rate of invasion	Does climate change favor cool season C3 or warm season C4 plants?	Rangeland health (grazing regime, vigor, carryover, drought tolerance)	See changes in wildlife populations quickly in extremes
	Rx fire feasibility (to control invasives)	Cedar encroachment	Expansion of willow into meadows	

Wetland resources & functions::

Initial candidates	**Wetland permanence (e.g., proportion of wetlands that are permanent, seasonal, etc.)**	**Total lake & wetland area**	**Runoff/ streamflow**	**Groundwater recharge**
Other potential metrics	Invasive plant species; are new species showing up, or is there a change in rate of invasion	See changes in wildlife populations	Extent of open water and emergent vegetation (hemi marsh)	Water quality and quantity of submergent aquatic vegetation
	Plant composition (native/invasive, emergent/submergent, etc).	Groundwater level	Channel/floodplain connectivity	Impacts to Ogallala aquifer (where most sandhills water comes from)

Identifying climate sensitivities

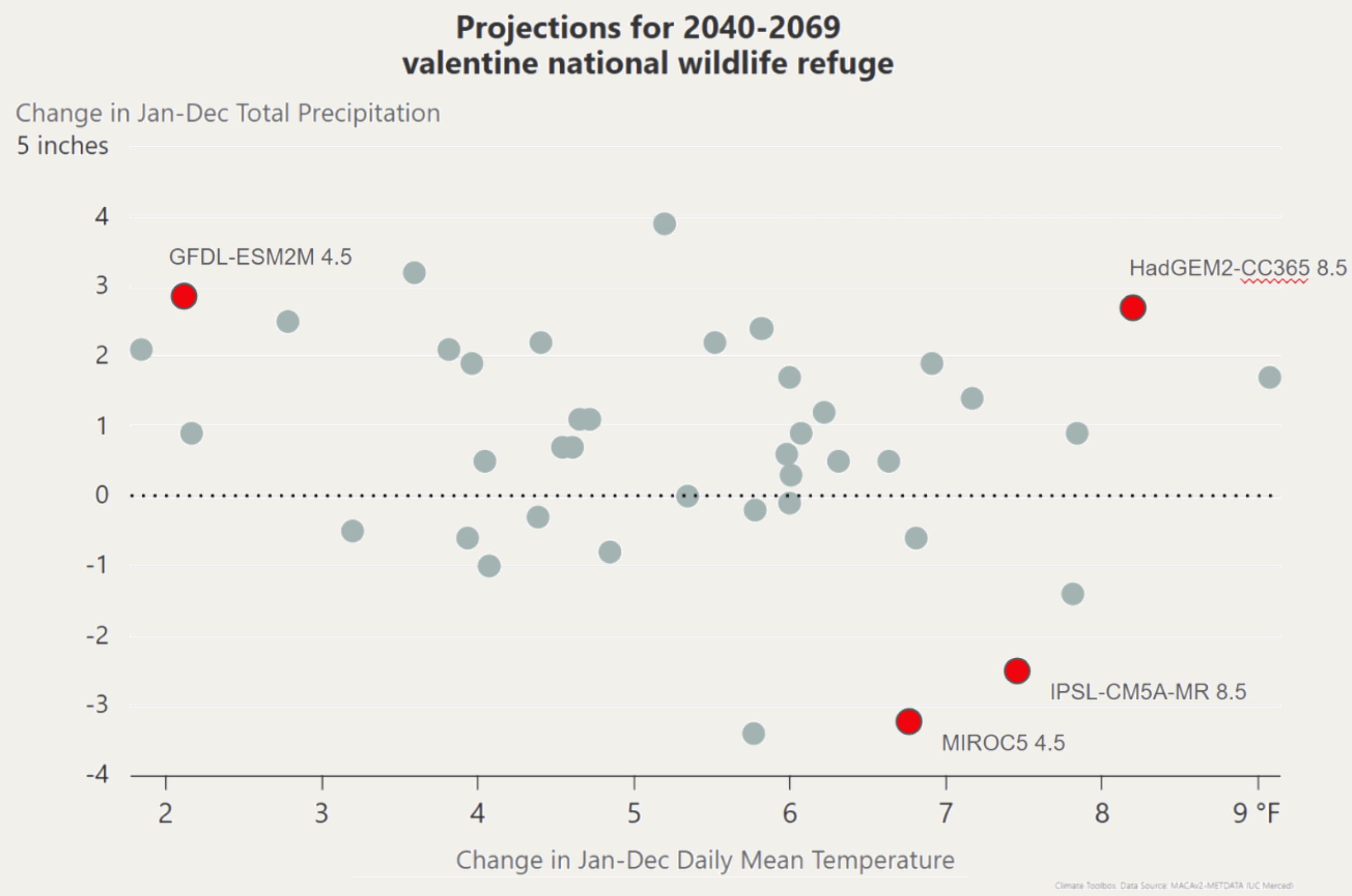
INSTRUCTIONS: Please review this matrix of climate and non-climate factors that influence priority ecological features in the Sandhills. Grey shading indicates that the ecological feature in that row is sensitive to the climate metric in that column. At the top, blue highlighting indicates climate metrics that may be influential across a number of ecological features or are very important for key features (e.g., groundwater), which we will focus on as we explore the divergence among climate projections. Add your initials in the row below (highlighted in yellow) to "vote" on which climate metrics are the highest priority to consider in future scenarios. You may also add your initials in other rows to indicate agreement with identified climate sensitivities for each ecological feature shaded in grey or to flag other metrics that may be important. Please use a comma between initials from multiple people.

CLIMATE SENSITIVITIES

Priority ecosystem	CCP communities	ESDs	Associated species	Ecological feature or function	Specific metrics or components of each ecological feature
VOTING: use this row to add your initials under climate metrics that you see as critical to focus on in future projections					
Sandhills Grasslands	***Crescent:*** Upland Habitat, Sands, Choppy Sands, and Sands/Choppy Sands Mixed Habitats. ***La Creek:*** Sandhills. ***Valentine:*** Grasslands, Sandhills Prairie. ***Ft. Niobrara:*** Sandhills Prairie, Mixed Prairie, Tallgrass Prairie	Choppy Sands, Sands, Sandy, Sandy Lowland, Subirrigated, Wet Subirrigated	***Birds:*** Burrowing owl [vclf], Ferruginous hawk [vclf], Loggerhead shrike [vclf], Long-billed curlew [vclf], Short-eared owl [vclf], Greater prairie-chicken [vclf], Sharp-tailed grouse [vclf], Western meadowlark [vclf], Grasshopper sparrow [vclf], Dickcissel [vlf], Northern harrier [vlf], Northern pintail [vcl], Blue-winged teal [vcl], Mallard [vcl], Golden eagle [vl], Lark bunting [lf], Chestnut-collared longspur [vf], Upland sandpiper [vf], American wigeon [vl], Gadwall [vl], Swainson's hawk [v], Savannah sparrow [l], Vesper sparrow [l], Baird's sparrow [v], McCown's longspur [v], Bobolink [f], Eastern meadowlark [f], Northern shoveler [l]. ***Plants***: Blowout penstemon (Federal Endangered) [vc], Western prairie fringed orchid [v], other rare native plants [v]. ***Invertebrates:*** Monarch butterfly [vclf], Regal fritillary butterfly [vlf], American burying beetle (Federal Endangered) [vf], Iowa skipper [f], Mottled duskywing [f], Ottoe skipper [f], Bombus sp. and other native bees/pollinators [c]. ***Amphibians:*** Leopard frog [v], Tiger salamander [v]. ***Reptiles:*** Blanding's turtle [v], Lesser earless lizard [v], Prairie lizard [v], Six-lined racerunner [v]. ***Mammals:*** Bison [f], Elk [f].	Grassland structure (height, density, litter, bare ground)	**Productivity**
				Native plant diversity	**Warm-season native grasses**
					Cool-season native grasses
					Forbs
				Cedar encroachment	**Tree density/cover; demographic rates**
				Invasive plant abundance	**Perennial cool-season invasive grasses (smooth brome, Kentucky bluegrass)**
					Annual cool-season invasive grasses (cheatgrass)
				Fire management	**Burn window**
Wetlands	***Crescent:*** Wetland Habitat (lakes and marshes), Natural Lakes, Artificially Managed Lakes. ***La Creek:*** Developed Wetlands. ***Valentine:*** Fens, Temporary, Seasonal, Semipermanent and Permanent Wetlands, Lakes. ***Ft. Niobrara:*** Niobrara River and Streams, Seeps and Springs, Palustrine Emergent Wetlands, Riparian Forest/ Palustrine Wooded Wetlands		***Birds:*** Trumpeter swan [vclf], American bittern [vcl], Black rail [vcl], Black tern [vcl], Black-crowned night-heron [vcl], Double-crested cormorant [vcl], Eared grebe [vcl], Forster's tern [vcl], Interior least tern (Federal Endangered) [vlf], Marsh wren [vcl], Sora [vcl], Virginia rail [vcl], White-faced ibis [vcl], Whooping crane (Federal Endangered) [vlf], Yellow-headed blackbird [vcl], Canvasback [vcl], Common merganser [vlf], Redhead [vcl], Ruddy duck [vcl], Ring-necked duck [vl], Sandhill crane [vl], Western grebe [vl], Bufflehead [vl], Lesser scaup [vl], Swamp sparrow [v], Clark's grebe [v], Sedge wren [l], American avocet [c], American white Pelican [l], Bald eagle [f], Blue-winged teal [f], Canada goose [f], Common goldeneye [f], Mallard [f], Piping plover [f], Spotted sandpiper [f], Wood duck [f]. ***Invertebrates:*** Monarch butterfly [vf], Regal fritillary butterfly [vf], Iowa skipper [f], Mottled duskywing [f], Ottoe skipper [f]. ***Amphibians:*** Leopard frog [v], Tiger salamander [v]. ***Reptiles:*** Blanding's turtle [v], Yellow mud turtle [vc]. ***Fish:*** Blacknose shiner [vf], Finescale dace [vf], Northern redbelly dace [vf], Plains topminnow [vf], Bigmouth chub [f], Brook stickleback [f], Creek chub [f], Longnose dace [f], White sucker [f].	Hydroperiod	**Wetland permanence**
				Groundwater recharge, groundwater level	**Well level**
				Native plant composition	**Aquatic vegetation; wet meadow vegetation (grasses, sedges)**
					Willow
				Invasive plant abundance	**Phragmites; hybrid cattail; reed canary grass**
				Total lake/wetland area	**Surface water extent**
				Channel/floodplain connectivity	**Incisement**

	Overall moisture availability			Seasonal precipitation/ moisture					Climate Extremes						Heat					Non-climate factors							
	Annual precipitation	Cumulative precipitation (5-yr)	Annual water balance (P - ET or P/PET)	Fall/winter precip	Spring precip	Summer precip	Growing season (Apr-Aug) precipitation or water balance	Growing season soil moisture	Intense rainfall events	Precipitation variability	Flooding	Short-duration drought (June/July)	Long-duration pluvial (multi-year)	Long-duration drought (multi-year)	Mean annual temperature	Potential evapo-transpiration	Growing season start date	# hot days	Windspeed	Groundwater level	Elevated CO2	N enrichment	Grazing management: timing, intensity	Fragmentation	Agriculture (draining, haying, irrigation)	Woody Encroachment	Fire (prescribed or wildfire)
VOTING			MF, SK, MN		MF, SK	MF, SK	SK, MN			MF, SK							SK	MF, MN									

Selecting climate futures

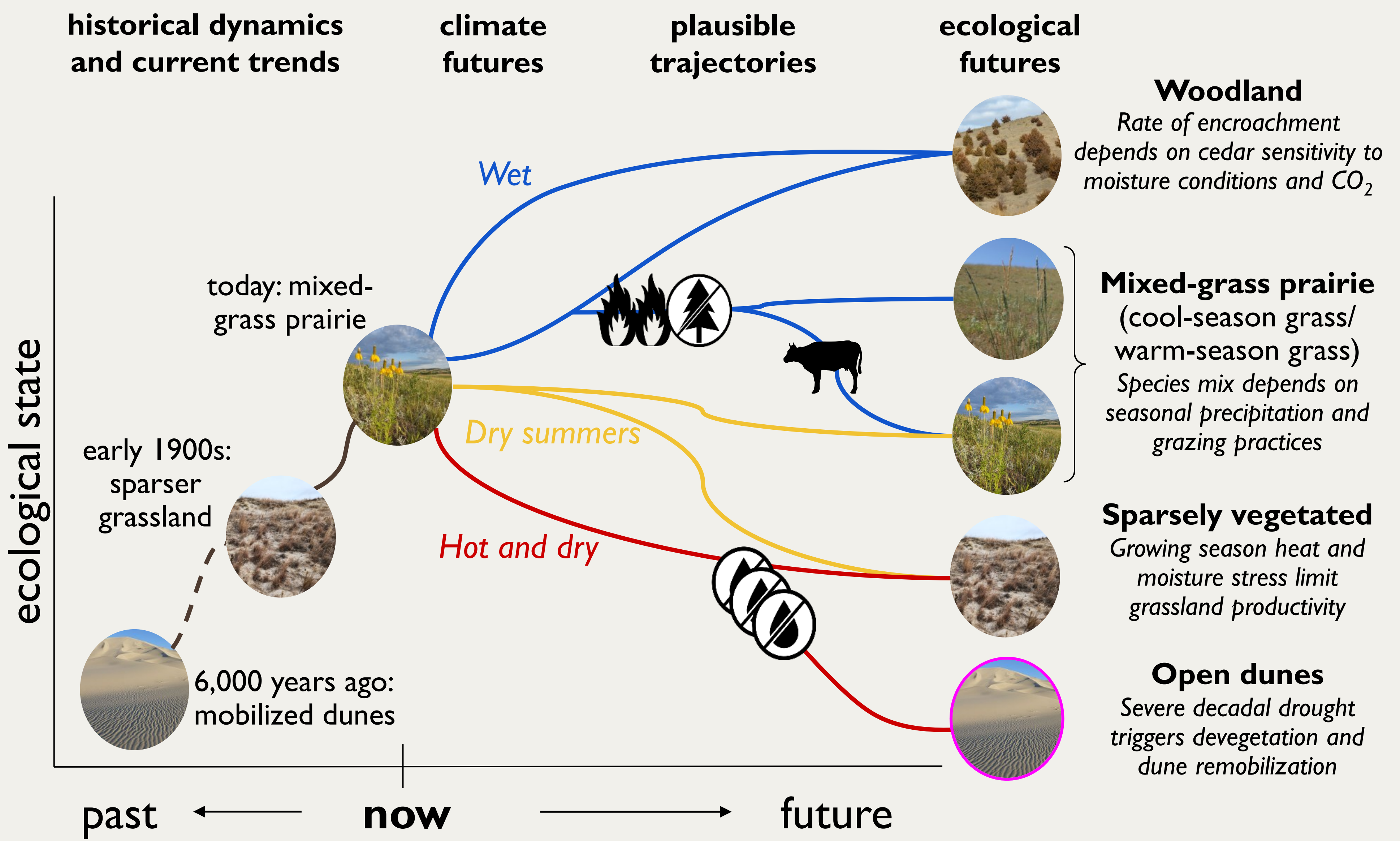


Relative Change: -1.0 -0.5 0.0 0.5 1.0

	Historical	GFDL	HadGEM2	IPSL	MIROC5
Summer Climatic Water Deficit	5.7	5.8	8.7	11	10.1
Spring Runoff	1.2	1.8	1.2	0.8	0.5
Spring Climatic Water Deficit	0.6	1.1	0.9	1.8	2.5
Annual Soil Moisture	1.7	1.7	1.6	1.2	0.9
Annual Climatic Water Deficit	8.2	9.2	13.3	15.9	15.8
Annual Mean Temperature	48.6	50.9	56.7	55.9	54.7
Length of Growing Season	153.1	157.9	193.1	180.7	179.5
Day of Last Spring Freeze	5/1	-2	-19	-12	-17
Day of First Fall Freeze	10/1	3	21	16	9
Winter Precipitation	1.4	1.4	2.1	1.6	1.4
Summer Precipitation	8.6	9.2	7.8	6.5	7.4
Spring Precipitation	7	8.3	9.4	6.9	5.9
Fall Precipitation	4.1	4.2	3.9	4.3	3.8
Annual Precipitation	21.1	23.1	23.2	19.4	18.5
Annual Wind Speed	10.1	10	9.7	9.8	10.2
Hottest Summer Day	101.1	101.6	108.4	109.3	109.2
Days With Max. Temperature Above 86F	56.5	71.3	99.5	103.5	99.1
Coldest Winter Day	-14.4	-10	-1.8	-5	-7.4

"Warm wet" "Hot wet" "Dry summers" "Hot dry"

Putting it all together: Sandhills Ecological Responses



Current trends, DGVM projections

Ecoregion analogs, Expert knowledge

Historical trends

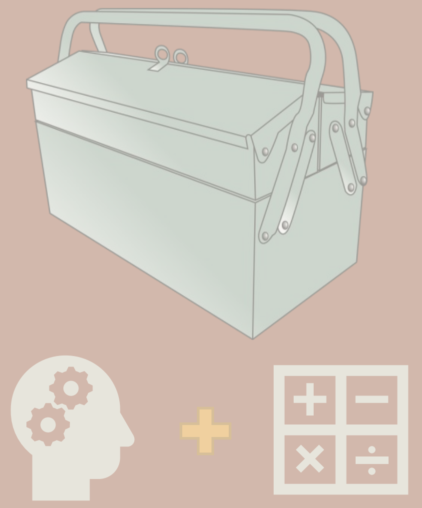
Paleo reconstructions, process-based modeling

Clark-Wolf et al. 2025 *Ecosphere*

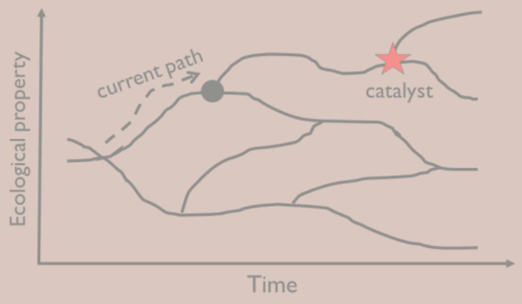
Photos: T. Walz, M. Lavin, C. Helzer, O. Richmond, NPS

What's Next?

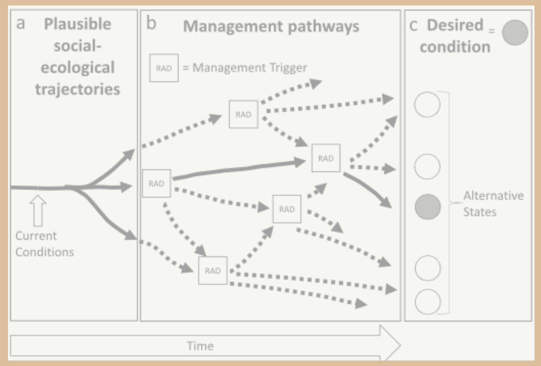
Building the toolbox



Research



Practice



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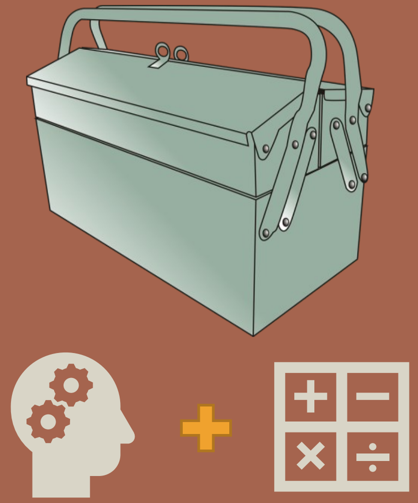
"Test driving" our approach

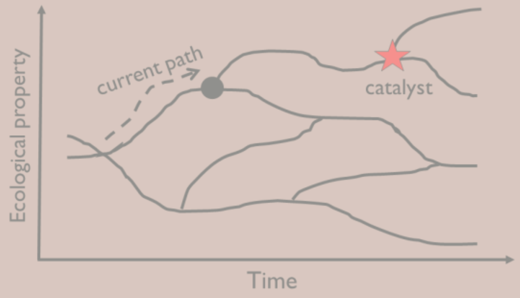
1. Refine Scenarios
2. Workshop with managers

What's Next?

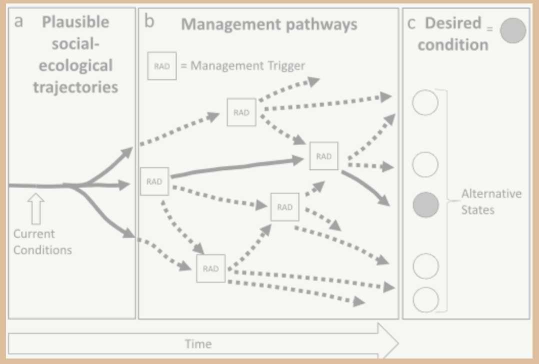
Building the toolbox



Research



Practice



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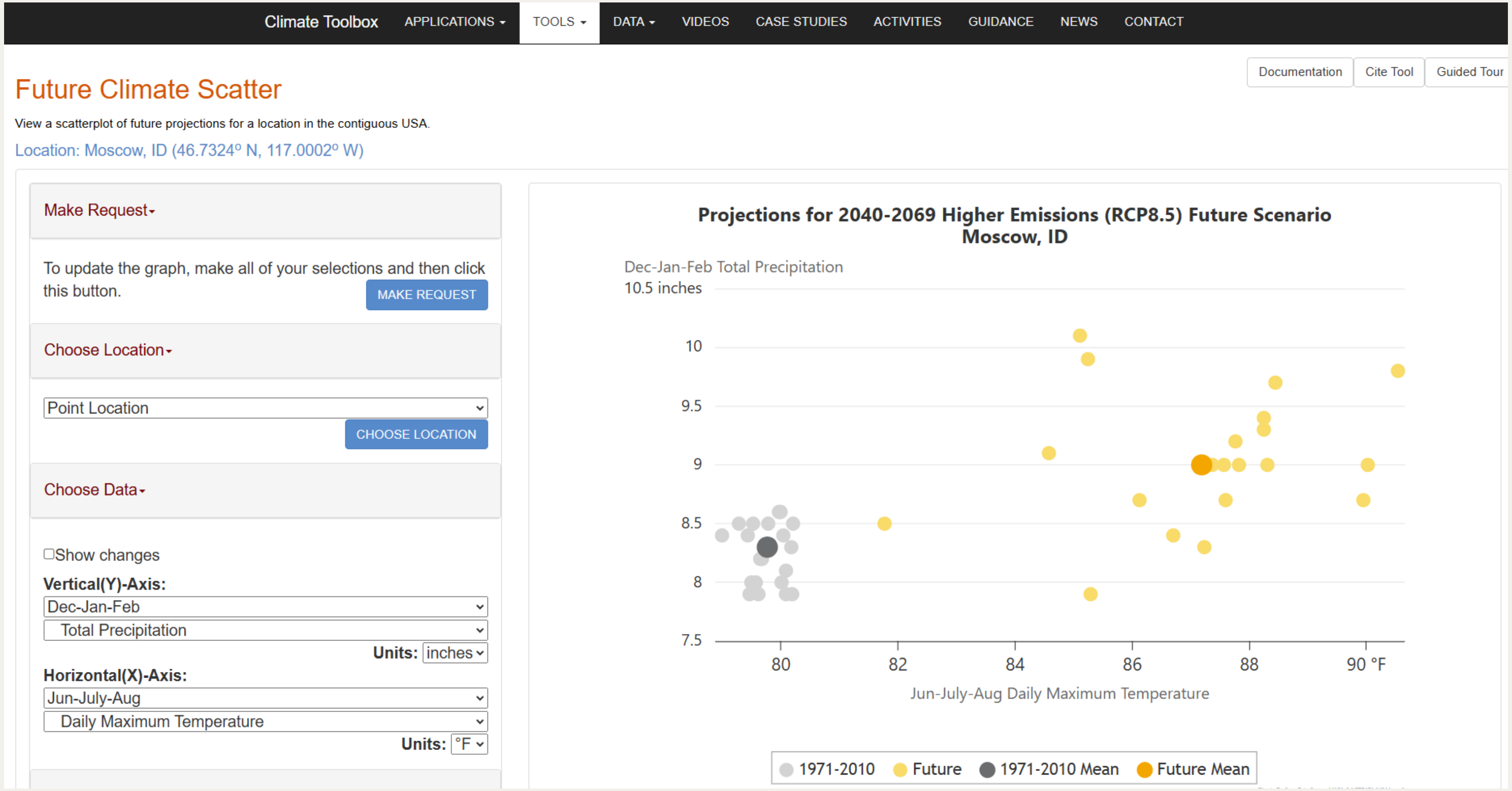
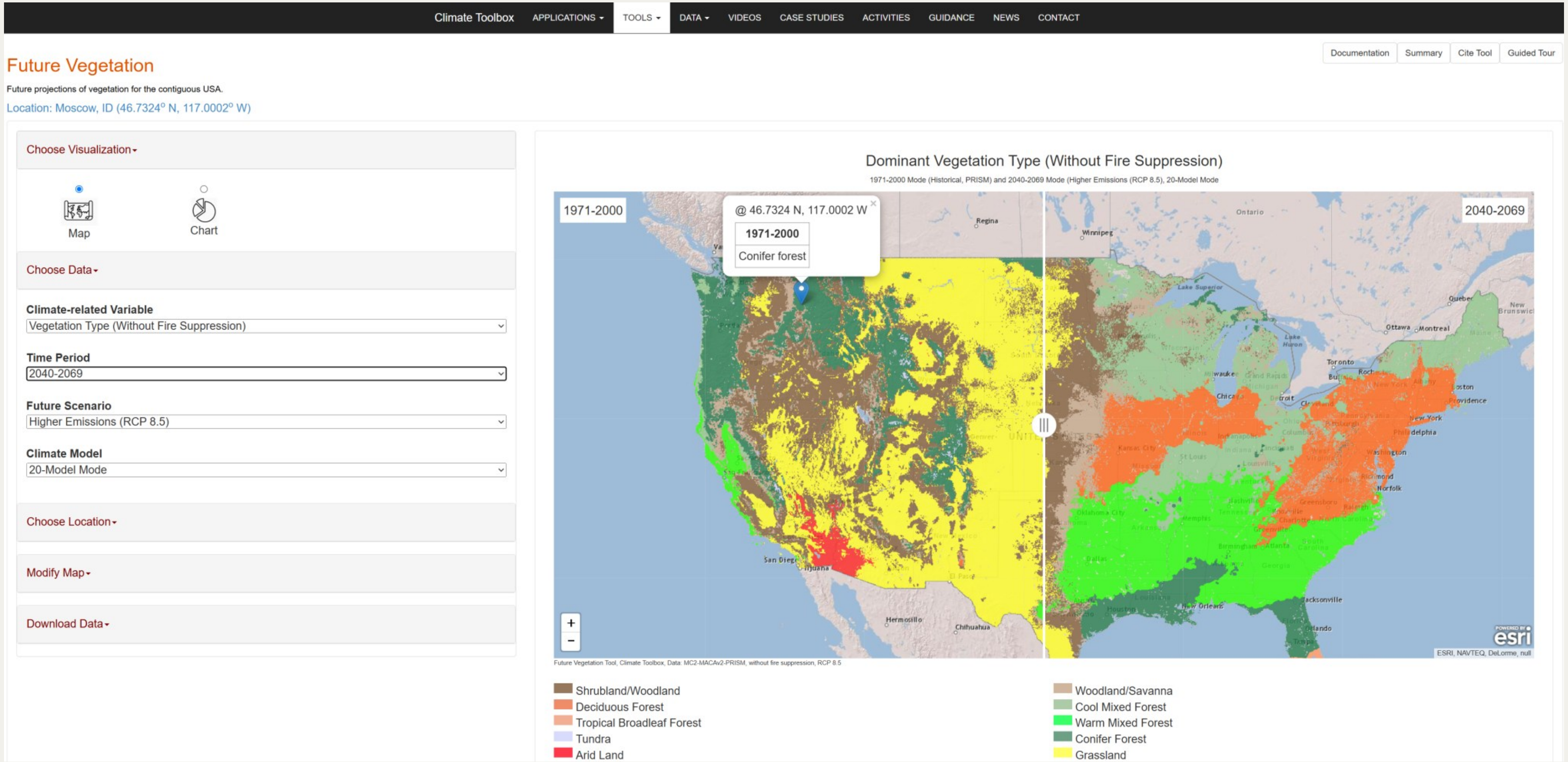
"Test driving" our approach

Existing Resources: The Climate Toolbox



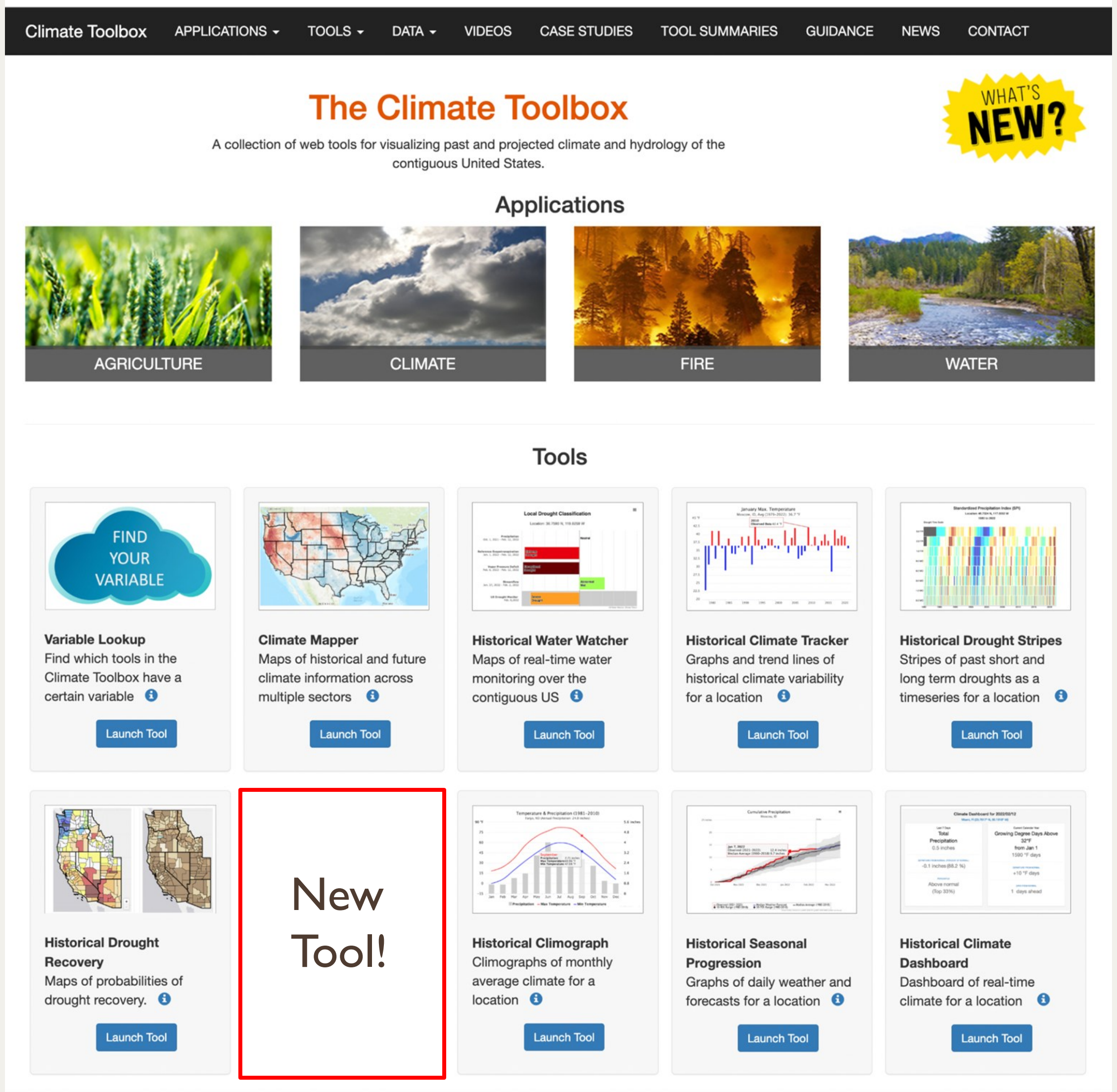
https://climatetoolbox.org/

Existing Resources: Future Vegetation Tool

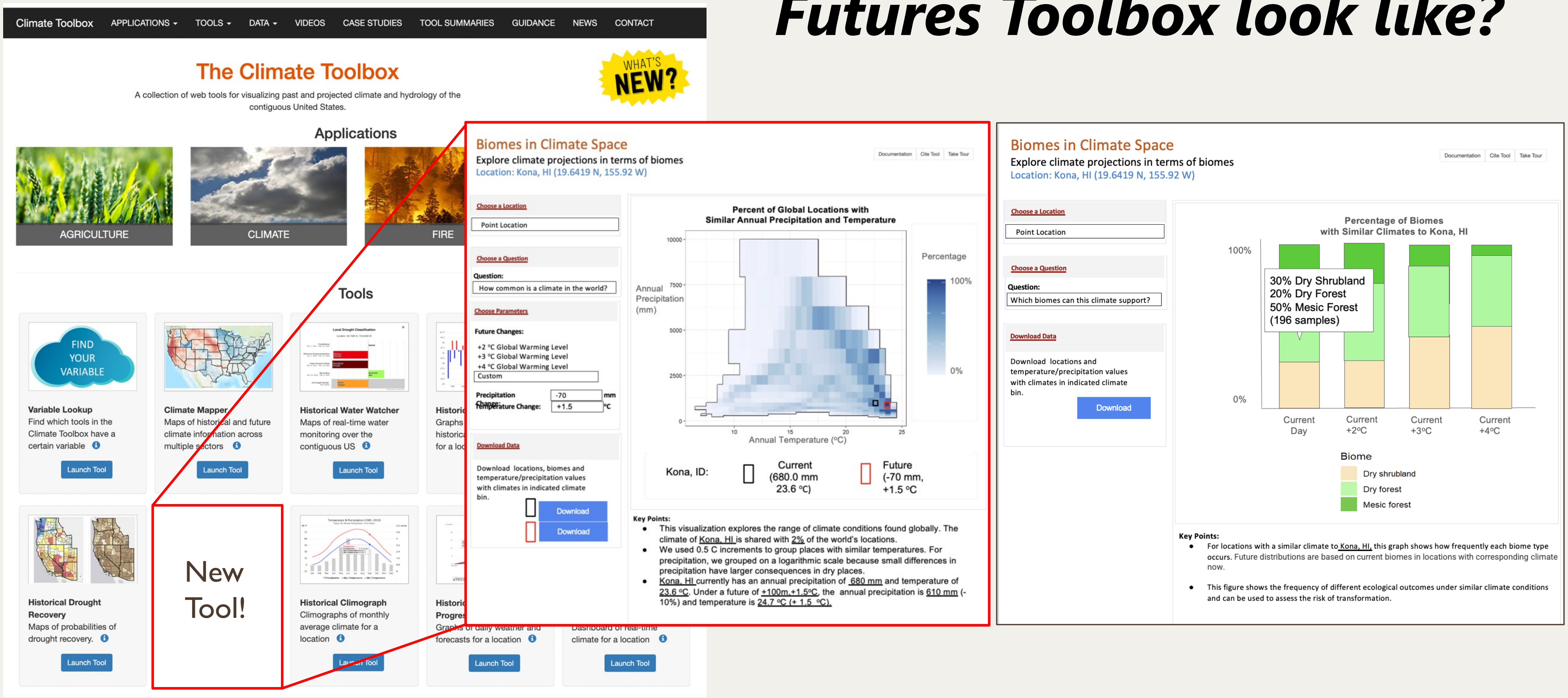


https://climatetoolbox.org/

What would an Ecological Futures Toolbox look like?



What would an Ecological Futures Toolbox look like?



Source: Helen Sofaer (USGS) and Katherine Hegewisch (UC Merced)

Preliminary information – subject to revision. Not for citation or distribution.

ECOSCENARIOS WORKSHOP

July 17-18, 2023 ~ Boulder CO

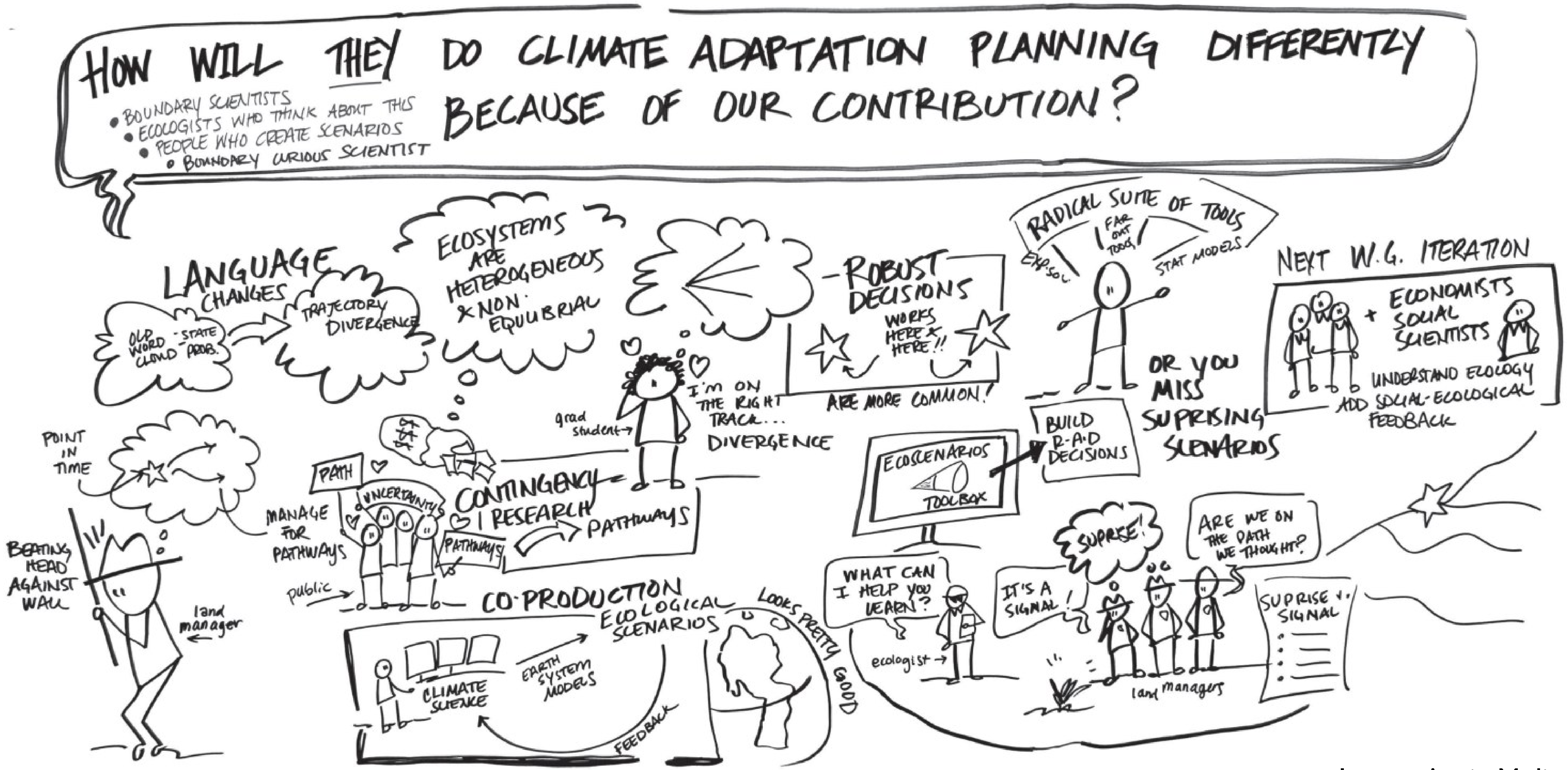


Image: Angie Moline

Questions?

1 University of Montana (UM)
Phil Higuera: co-PI; forest fire and vegetation dynamics

2 The Nature Conservancy (TNC)
Marissa Ahlering: co-PI; grassland ecology & climate change solutions (North/South Dakota)
Terri Schulz: co-PI; conservation planning, ecology & land management (Colorado)

3 University of Wyoming (UW)
Corrine Knapp: co-PI; climate adaptation, conservation innovation

4 Great Plains Tribal Water Alliance (GPTWA)
Reinique Beck: co-PI; Tribal water quality & management

5 University of Colorado Boulder (CU Boulder)
William Travis: PI; climate risk & adaptation
Jane Wolken: co-PI; forest ecology
Imtiaz Rangwala: co-PI; climate science & applications
Heather Yocum: co-PI; social science & JEDI programs
Laura Dee: ecosystem services responses to climate change
Kyra Clark-Wolf: ecological impacts & transformation
Chelsea Nagy: invasives, wildfire & ecological transformations
Ulyana Horodyskyj Peña: science communication & outreach
Hailey Robe: administration, communication & outreach
James Rattling Leaf, Sr.: Tribal engagement & ethical space framework (South Dakota)
Christy Miller Hesed: actionable science & ethnography management & ecology (Kansas)

6 South Dakota State University (SDSU)
Jeff Martin: co-PI; bison health, grassland ecology & management

7 Colorado State University (CSU)
Ana Davidson: co-PI; wildlife science & zoonotic diseases
Courtney Schultz: co-PI; fire, policy & collaboration

CIRES

University of Colorado Boulder

Contact: Kyra.Clark-Wolf@colorado.edu