

Appendix 2 Niwot Ridge Contributions to the Network Planning Grant

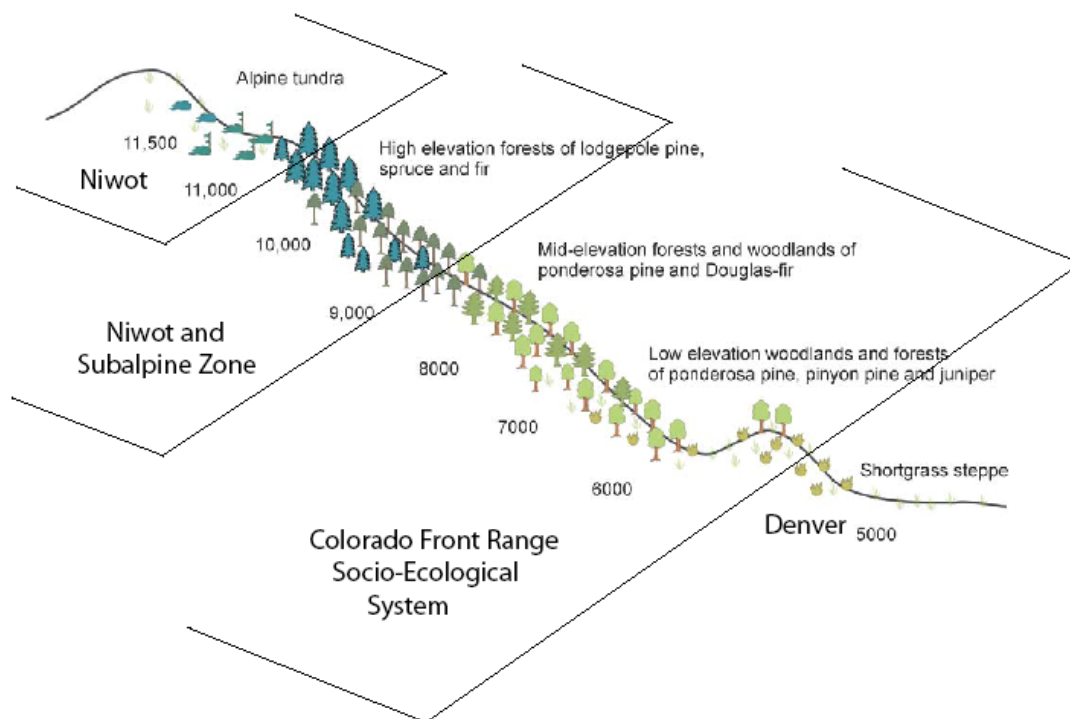
Interactions between Climatic Variability and Land-Use Change in the Colorado Front Range: A Multi-Scaled Approach

Patrick Bourgeron, Hope Humphries, Tim Seastedt, and Mark Williams
INSTAAR, University of Colorado at Boulder

Niwot Ridge Multiscaled Approach

The approach presented is multi-scaled, from the Niwot Ridge LTER site (landscape level) to the subregional and regional levels. NWT LTER represents a challenge and a unique contribution to the LTER network because of the seemingly isolated location of its high elevation alpine terrestrial and aquatic ecosystems. NWT is relatively pristine, yet is located in a subregion and region that have experienced dramatic changes since the mid 19th century, especially in the last decades due to rapid demographic changes. Traditionally, influences across ecosystems were considered as predominantly a top down process along an elevation continuum (Seastedt et al., 2004). However several key drivers of change at NWT originate from other levels and force us to expand on the nature of the interactions across scales.

Figure 1. NWT spatial scales of interest.



We have identified three nested levels (Figure 1) for developing feedback loops. These three levels comprise NWT LTER, the alpine-subalpine area, and the Colorado Front Range forested area. The feedback loops developed for each level serve as a framework for integrating social

and natural sciences at NWT and surrounding areas, as a basis for collaboration with other LTER sites at the appropriate levels of the questions, and as a basis for linking LTER research and the NEON data stream.

The three identified levels presented in Figure 1 illustrate the contribution of NWT LTER in defining cross-level (scale) interactions. Our approach uses and expands on the continuum concept developed for NWT.

For each feedback loop, we developed specific versions of the generic LTER model. These generic questions are:

Q 1: How do long-term press and short-term pulse disturbances interact to alter ecosystem and function?

Q 2: How can biotic structure be both a cause and consequence of fluxes of energy and matter?

Q 3: How do altered ecosystem dynamics affect ecosystem services?

Q 4: How do changes in vital ecosystem services feed back to alter human behavior?

Q 5: Which human actions influence the frequency, magnitude, and form of press and pulse disturbance regimes within and across ecosystems?

The feedback loop indicates for each level potential points of interaction with the LTER network: snow amounts and distribution (e.g., Arctic, Bonanza, Harvard Forest, and Hubbard Brook); fire (Cedar Creek, Coweeta, Florida Coastal Everglades, HJ Andrews, Jornada, Sevilleta, and Short Grass Steppe); and land use change, including suburbanization and exurbanization (most of the already cited LTER, Baltimore Ecosystem Study, and Central Arizona-Phoenix).

Level 1: Niwot (including Green Lakes valley and the forest-alpine tundra ecotone)

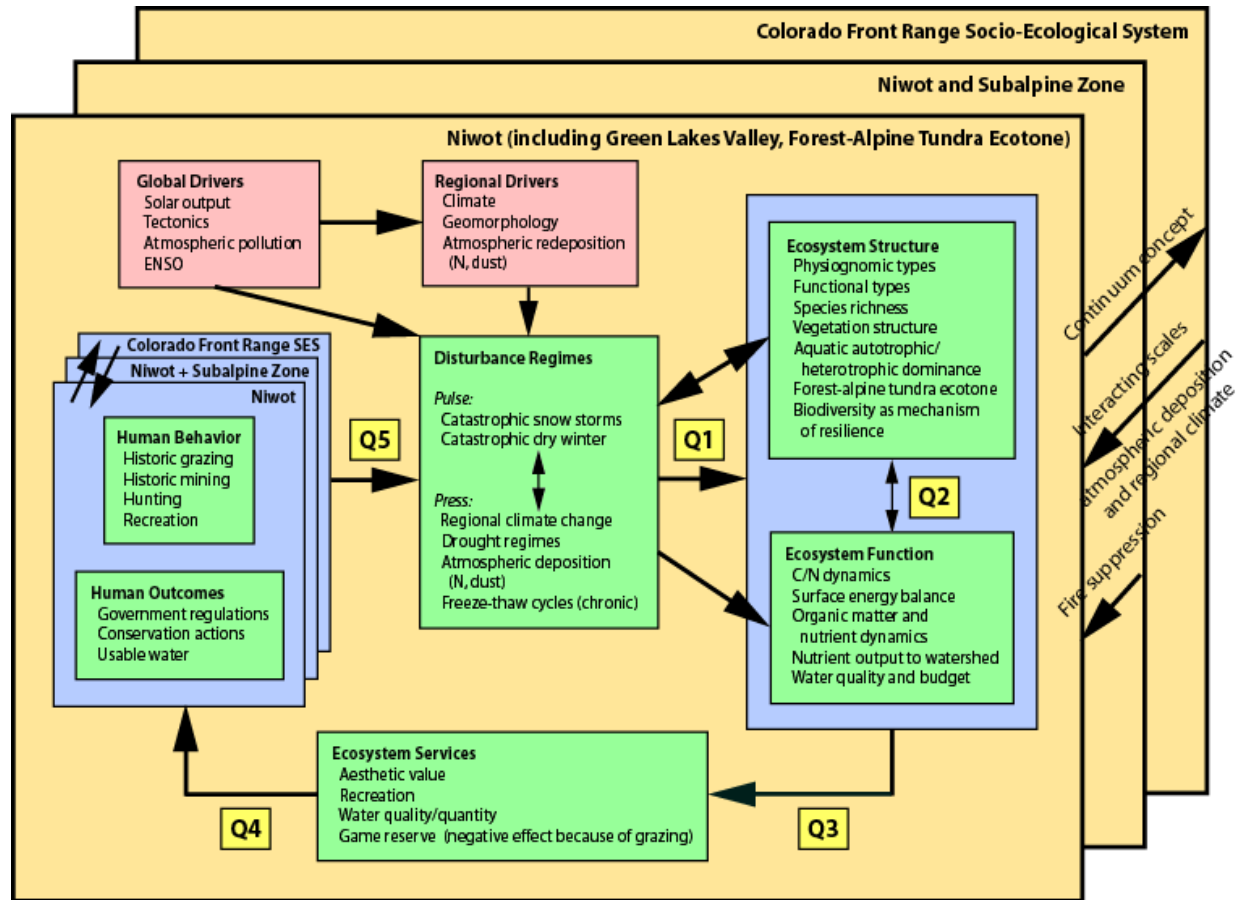
Narrative:

The feedback loop (Figure 2a) for Niwot (hereafter called NWT-L1) illustrates how human systems interact with seemingly pristine and remote ecosystems. Figure 2b reflects the influence of human behavior and outcomes on the feedback loop (Q4 and Q5) at the three levels of interest to emphasize the scale relations of the social dimensions on NWT-L1. Temperature and snowfall are two key structuring drivers of high elevation alpine ecosystems. Changes in temperature and amounts and distribution of snowfall due to climate change, as well as atmospheric deposition due to human activities in the Colorado Front Range, could strongly influence the dynamics of these high elevation ecosystems. Changes in snow cover and duration affect the dynamic linkages between hydrological budgets and biotic structure (Q2). Vegetation, topography, and geomorphology interact with snowfall to determine the timing and spatial patterns of snow accumulation and melting (Q1). A combination of regional (Front Range) and global human decisions and actions influence natural disturbance regimes (Q4, Q5). Changes in disturbance regimes alter the dynamic linkages between ecosystem structure and function. Whether the feedback of biotic structure to disturbances is positive or negative could affect thresholds in ecosystem responses to change (Q1, Q2). Changes in hydrological budgets (Q1) affect the movement and dynamics of materials and may affect the threshold behavior of ecosystem structure (landscape distribution and structure of biotic communities; Q2). These

changes and the extent to which they influence changes in the ecotone have implications for ecosystem services (Q3). In particular, hydrological budgets in alpine ecosystems, and whether treeline is moving upward into the alpine zone, have complex effects on the quantity and quality of water. Changes in this ecosystem service would have a major impact on the increasingly urban population of the Front Range and farming communities (Q4).

The Feedback Loop Questions (Figures 2 a, b):

Figure 2a. NWT-L1 socio-ecological system.



- Q1: How do long-term trends in climate and atmospheric deposition interact with extremes in snowfall (catastrophic storms, catastrophic dry winter) to influence ecosystem structure and function?
- Q2: How are the feedbacks between landscape patterns and community structure (vegetation, animals, and soil microbial communities) and functioning (ecosystem and hydrological budgets) affected by change in the quantity and timing of snowfall and interactive influences with other pulse/press disturbances?
- Q3: How do ecosystem state changes caused by changes in climate and atmospheric deposition affect aesthetic values and water quantity and quality?
- Q4: How do the residents of Colorado and the increasing numbers of users of high elevation ecosystems services (particularly recreation and water use) perceive and/or use these ecosystem services; how will these perceptions affect their current and projected use of these ecosystem services; specifically, how will their perceptions change, or how willing are they to alter their behavior, in response to changes in these services and/or their regulation?
- Q5: Which combination of individual and institutional decisions and actions affect the interactions between pulse/press disturbances and snowfall, temperature, and atmospheric deposition?

Q 1: How do long-term trends in climate and atmospheric deposition interact with extremes in snowfall (catastrophic storms, catastrophic dry winter) to influence ecosystem structure and function?

We have two general questions concerning the interactions between pulses/presses and a feedback loop between these and ecosystem structure:

1. How do pulses in the timing and quantity of snowfall interact with long-term presses to influence threshold behavior and associated state changes in ecosystem structure and function?
2. How do changes in ecosystem structure interact with pulses to alter the influence of long term presses on ecosystem function (the feedback from structure to disturbances)?

The areas of inquiry concerning the influence of pulses and presses include:

- Ecosystem structure:

Question: How do changes in the quantity and timing of snowfall and interactive influences with other pulses/presses influence the ecosystem structure of terrestrial and aquatic communities (e.g., impacts of changes in snow pack and consequent water flow paths on plant community species composition, physiognomy, and functional type)?

Specific areas of investigation include impacts on the structure of plant communities (species composition: do some species increase or decrease?), stand physiognomy (graminoid, cushion/upright forb, shrub) and the structure of aquatic communities (autotrophic/heterotrophic dominance).

- Ecosystem function:

Question: How do changes in the quantity and timing of snowfall and interactive influences with other pulses/presses influence hydrological budgets, surface energy balance, nutrient cycling, and evapotranspiration?

Specific areas of investigation include impact on surface energy balance, OM and nutrient dynamics, and C/N dynamics.

Q 2: How are the feedbacks between landscape patterns and community structure (vegetation, animals, and soil microbial communities) and functioning (ecosystem and hydrological budgets) affected by changes in the quantity and timing of snowfall and interactive influences with other pulse/press disturbances?

- Ecosystem (biotic) structure as cause:

Question: How do changes in terrestrial and aquatic community structure (as in Question 1), such as changes in species composition, vegetation physiognomy and functional type, food webs, and autotrophic/heterotrophic dynamics, influence hydrological budgets (via changes in ET, structural change in flow paths), C/N dynamics, and N dynamics?

Specific areas of investigation include the study of (1) biodiversity as a mechanism of resilience of NWT ecosystems and (2) landscape configuration as a mechanism of resilience of the ecotone.

- Ecosystem function as cause (biotic structure as consequence):

Question: How do changes in hydrological budgets, which affect ecosystem properties such as soil moisture and soil temperature, affect carbon fluxes and storage above and below ground and therefore the structure and spatial distributions of biotic communities?

Specific areas of investigation include the study of the influence of variability in hydrological budgets on the threshold behavior of ecosystem structure.

Q 3: How do ecosystem state changes caused by changes in climate and atmospheric deposition affect aesthetic values, recreation, water quantity and quality, and big game?

Figure 2b. NWT-L1 human behavior/outcomes scale relations.



Q 4: How do the residents of Colorado and the increasing numbers of users of high elevation ecosystems services (particularly recreation and water use) perceive and/or use these ecosystem services; how will these perceptions affect their current and projected use of these ecosystem services; specifically, how will their perceptions change, or how willing are they to alter their behavior, in response to changes in these services and/or their regulation?

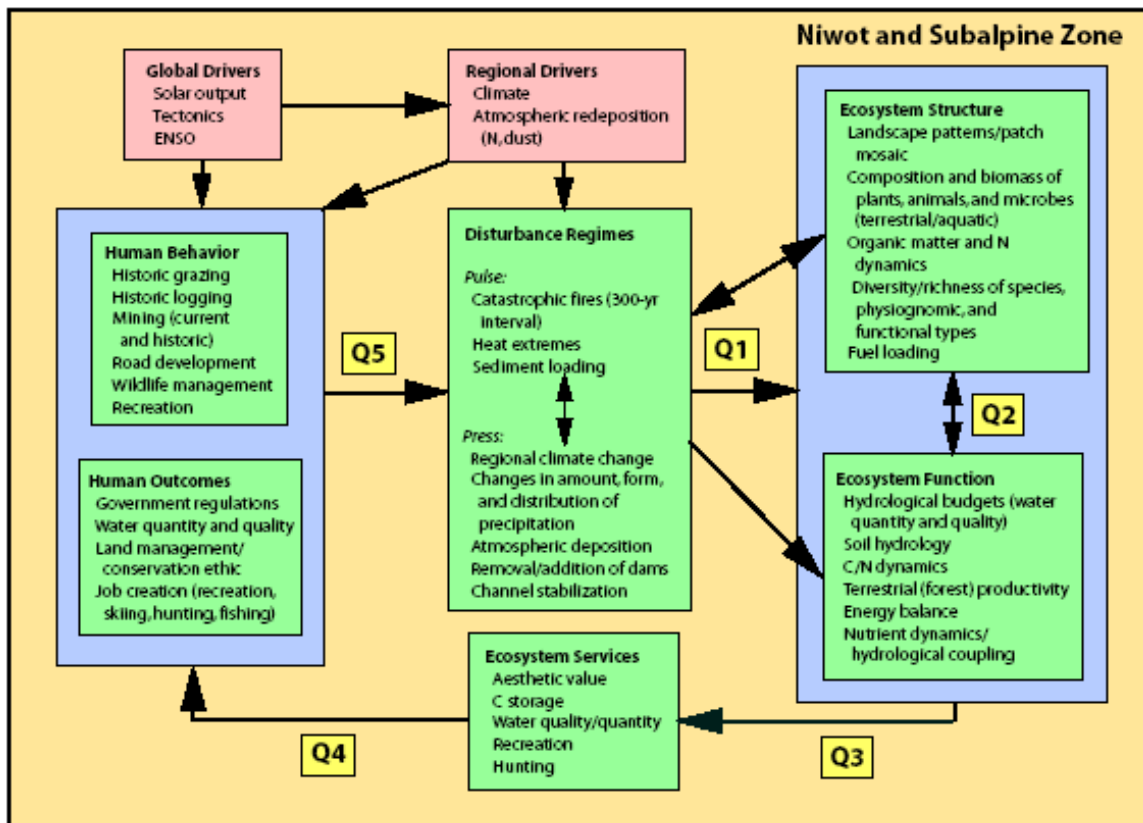
Q 5: Which combinations of individual and institutional decisions and actions affect the interactions between pulse/press disturbances and snowfall, temperature, and atmospheric deposition?

We have two general questions concerning human decisions and actions:

1. How do alternative scenarios of land use policies at lower elevations alter the presses and pulses that affect ecosystems and ecosystem services at the highest elevations?
2. What combination of educational, informational, and economic forces leads individuals to alter their behaviors to reduce negative impacts on ecosystems that are perceived as pristine and protected by their location?

Level 2: Niwot and Subalpine zone (SBA-L2)

Figure 3 illustrates the feedback loop.



Q1: How do long term trends in climate (warming); changes in amount, form, and timing of precipitation; atmospheric deposition; and disturbances to the land surface interact with periodic extremes to influence ecosystem structure and function?
 Q2: How are the feedbacks between landscape patterns and community structure (vegetation, animals, and soil microbial communities) and functioning (ecosystem and hydrological budgets) affected by changes in the quantity and timing of precipitation, changes in extreme temperatures, and interactive influences with other pulse/press disturbances?
 Q3: How do ecosystem state changes caused by changes in climate, atmospheric deposition and fire regimes affect aesthetic values, water quantity and quality, C storage, and recreation?
 Q4: How do the residents of Colorado and the increasing numbers of users of high elevation ecosystem services (particularly recreation and water use) perceive and/or use these ecosystem services; how will these perceptions affect their current and projected use of these ecosystem services; specifically, how will their perceptions change, or how willing are they to alter their behavior, in response to changes in these services and/or their regulation?
 Q5: Which human actions influence the frequency, magnitude, and form of press disturbances and their interactions with pulse disturbance regimes within and across ecosystems?

Figure 3. Niwot and subalpine zone (SBA-L2).

Level 3: Colorado Front Range Socio-Ecological System (COFRE_SES-L3)

Narrative:

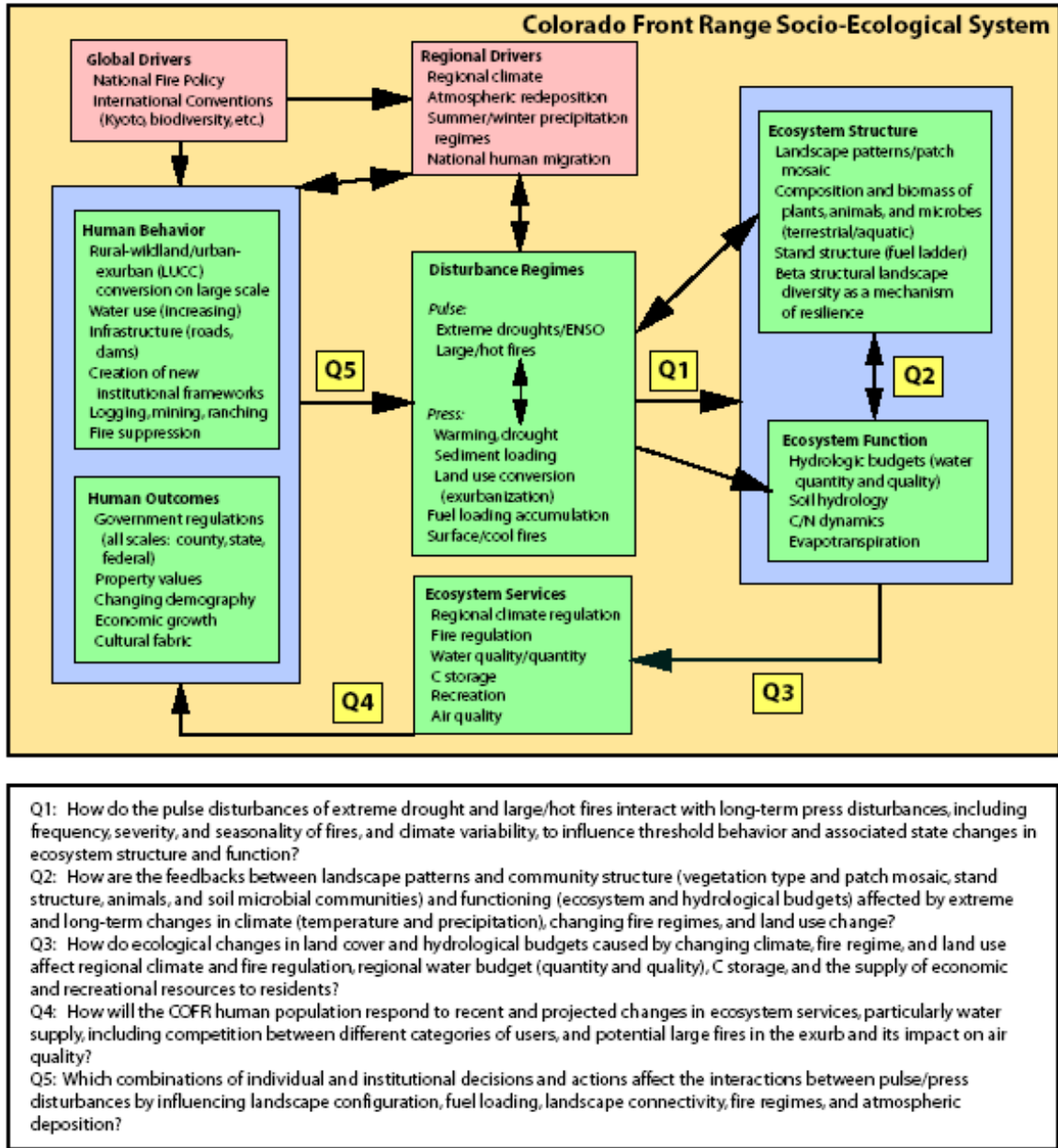
The feedback loop for the Colorado Front Range Socio-Ecological System (hereafter called COFR_SES-L3, Figure 4) illustrates how human systems interact with two key structural drivers of COFR mountain ecosystems. Patterns in temperature, the amount, timing, and form of precipitation, and landscape patterns of fire strongly influence the dynamics of COFR ecosystems. However, changes in climate variability, population increase, changing land use, and fire suppression combine to induce shifts in the structure and function of these ecosystems at all elevations and spatial scales (Q1). Extreme droughts combine with fuel loading increase (due to fire suppression, a function of federal, state and county fire policy) and land cover change (a function of land use change, such as exurban development, itself a function of the regional economy) to alter landscape patterns, stand structure, and hydrological budgets. Changes in landscape patterns and stand structure in turn create a positive feedback to fuel loading accumulation and therefore likely influence the threshold behavior of fire intensity and size. Changes in disturbance regimes alter the dynamic linkages between ecosystem structure and function (Q2). An example is the impact of fire suppression at lower elevations, which has eliminated short interval surface fires, leading to new successional trajectories, stand structures, and landscape patterns, thereby changing C/N dynamics (e.g., unburned sites retain N less effectively though decreased microbial immobilization), and soil hydrology (impact on aquatic ecosystems, e.g., changes in stream temperature inducing changes in the autotrophic/heterotrophic structure). Changes in landscape patterns and hydrological budgets have a potentially profound impact on all ecosystem services (Q3). In particular, the loss of fire regulation as a function of the landscape mosaic at low and mid elevations increases the need for fire suppression. In turn, fire suppression, which is concentrated near human communities, leads to further loss of fire regulation by the landscape (negative feedback) and increases long-term fire risk. Intense fires, rather than surface fires, at low to mid elevations could have profound impacts on other ecosystem services, for instance, by increasing sediment loading thereby affecting water quality, and by releasing C into the atmosphere. The degree to which there is close coupling between human understanding and human responses to perceived and projected ecosystem services (Q4) will determine the further influence of combined regional (COFR) and global human actions and decisions on disturbance regimes and their interactions (Q5). In particular, at low to mid elevations, where both urban and exurban development are taking place at a rapid pace, public opinion about fire risk and its consequences (as exhibited throughout the feedback loop) will drive the formulation and implementation of innovative fire policy, on both public and private land, by influencing county, state, and federal fire funding and policy. Long-term changes in the COFR SES will depend on the suggested socio-ecological interactions.

The Feedback Loop Questions (Figure 4):

Q1: How do the pulse disturbances of extreme drought and large/hot fires interact with long-term press disturbances, including frequency, severity, and seasonality of fires, and climate

variability, to influence threshold behavior and associated state changes in ecosystem structure and function?

Figure 4. Colorado Front Range socio-ecological system (COFRE_SES-L3).



Three examples of specific questions are: How do changes in fuel loading and stand structure interact with pulses to alter the influence of long-term presses on ecosystem function (the feedback from structure to disturbances)? How much do the spatial and temporal scales of land use changes match or differ from the spatial and temporal scales of historic disturbances (historic range of variability) and ecosystem responses to them (biological legacy effects)? How will the

increasing frequency, intensity, and spatial scale of fires alter regional climate (e.g., create a negative feedback to warming trends)?

Q2: How are the feedbacks between landscape patterns and community structure (vegetation type and patch mosaic, stand structure, animals, and soil microbial communities) and functioning (ecosystem and hydrological budgets) affected by extreme and long-term changes in climate (temperature and precipitation), changing fire regimes, and land use change?

- Ecosystem (biotic) structure as cause:

Question: How do changes in terrestrial and aquatic landscape configuration and community structure, such as changes in patch configuration, species composition, vegetation physiognomy and functional type, food webs, and autotrophic/heterotrophic dynamics, influence hydrological budgets (via change in ET, structural change in flow paths, fire spread patterns), C/N dynamics, and N dynamics?

A specific area of investigation would include the study of landscape configuration and diversity as a mechanism of resilience to fire spread and associated changes in ecosystem function.

Another area of investigation concerns how changes in connectivity among ecosystem components (as a result of fire suppression, roads, dams, and forest harvest patterns) impact the resilience of native communities and species to the introduction of exotic species.

- Ecosystem function as cause (biotic structure as consequence):

Question: How do changes in hydrological budgets and soil hydrology, which affect ecosystem properties such as soil moisture and soil temperature, affect carbon fluxes and storage above and below ground and therefore the structure and spatial distributions of biotic communities?

A specific area of investigation includes the study of the influence of variability in hydrological budgets on the threshold behavior of ecosystem structure.

Q3: How do ecological changes in land cover and hydrological budgets caused by changing climate, fire regime, and land use affect regional climate and fire regulation, regional water budget (quantity and quality), C storage, and the supply of economic and recreational resources to residents?

Specific questions of interest include the following. Do forest ecosystems decrease their water use in response to protracted or extreme drought, thereby mitigating the impact of reduced water availability on water quantity? How does altered fire frequency affect these dynamics (via change in landscape configuration, change in soil hydrology)?

Q4: How will the COFR human population respond to recent and projected changes in ecosystem services, particularly water supply, including competition between different categories of users, and potential large fires in the exurb including air quality impact?

A line of inquiry would be how willing are the increasing urban, suburban and exurban populations to alter their behavior in response to changes in these ecosystem services and/or their regulation?

Q5: Which combinations of individual and institutional decisions and actions affect the interactions between pulse/press disturbances by influencing landscape configuration, fuel loading, landscape connectivity, fire regimes, and atmospheric deposition?

A specific question would be: How will the combination of individual and institutional responses in the Colorado Front Range affect the sensitivity of fire, hydrological, and carbon storage systems to climate change presses and pulses?