Pepperwood

Inspiring conservation through science

A Climate Ecosystem Sentinel Site
Pepperwood Preserve

Sonoma County, California, USA

July 2019

Tosha Comendant, Ryan Ferrell, Michelle Halbur,
Morgan Gray, Steven Hammerich, and Lisa Micheli

A Dwight Center for Conservation Science **Technical Report**

Table of Contents

Introduction 4

Key Objectives 6

Research, Inventory, and Monitoring Activities 8

Climate, Soils, and Hydrology 8

- Weather Stations 9
- Fog and Atmospheric Deposition 10
- Soil Properties and Nutrient Cycling 13
- Soil Moisture 15
- Springs, Ponds, and Groundwater 16
- Stream Monitoring 18

Vegetation 21

- Stephen J. Barnhart Herbarium 22
- Phenology 23
- Fuel Moisture 24
- Grasslands 25
- Forests 27
- Chaparral 28

Wildlife and Connectivity 29

- Mammals 30
- Birds 33
- Reptiles and Amphibians 34
- Invertebrates 35

Emergency Alert Systems 36

- Alert Wildfire Camera 36
- Sonoma Water Emergency Alert Rain Gauge 37

Pepperwood Radio Communication Network 38

Cloud-based Data Management Platforms 39

Remote Sensing and Geographic Information Systems 41

Summary and Next Steps 42

Acknowledgements 44
References 45
Appendices 49
Appendix A: Pepperwood Science Questions 49
Climate and Hydrology 50
Vegetation Ecology 52
Wildlife and Corridor Ecology 54
Restoration Ecology and Stewardship 55
Atmospheric Pollution 56
Remote Sensing and Biogeography 57
Fire Science 57
Education and Stakeholder Engagement 58
Appendix B: Pepperwood Data Management Process 59
Data Management Plan Template 59
Appendix C: Sentinel Site Sensors by Location 65
Appendix D: Sentinel Site Field Station Background 72

Introduction

Pepperwood is a 3,200-acre preserve located near Santa Rosa in the inner Coast Ranges of California (Sonoma County). Pepperwood was originally founded as a field station of the California Academy of Sciences and has been owned and managed by the Pepperwood Foundation since 2005. The preserve's terrain is representative of the region's inland watersheds and is located at the headwaters of five creeks (Brooks, Mark West, Porter, Upper and Lower Franz Creek) that drain into the Russian River. The Pepperwood Foundation utilizes the property as a living laboratory to support conservation research, education, and community engagement.

Starting in 2010, Pepperwood has been building a *Sentinel Site* to systematically measure climate, hydrology, and ecosystem health in order to improve our understanding of how changes in climate affect our natural resources and communities. The ultimate science question we aim to answer is how our local watersheds and ecosystems respond to seasonal and long-term temporal and spatial climate variability, which informs a range of sub-questions across natural science disciplines (see *Appendix A: Pepperwood Key Science Questions*). Will some sites on the landscape change more or less than others over time; and will the spatial heterogeneity, key to our region's biodiversity, collapse or expand in the future? Our results have broad applicability to understanding how climate variability drives processes in Mediterranean ecosystems world-wide, and in turn, how to best manage land, water and wildlife in these highly biodiverse natural, working, and rural residential landscapes.

Sentinel Site is a term utilized by the US National Oceanic and Atmospheric Administration (NOAA) and others to describe efforts dedicated to accurately monitor physical and biological conditions over time. The NOAA Sentinel Site Collaboratives unite science, management, and technology to measure rates and processes associated with sea-level rise to inform coastal climate adaptation strategies. Sentinel Sites combine data collection, community education, and local agency engagement to develop innovative place-based resource management solutions. Our goal is to model how to integrate climate, hydrology, and biology data collection at an inland, freshwater Sentinel Site to improve our understanding of trends and interactions between climate, watershed processes, and ecosystem health.

Pepperwood's Sentinel Site design described here is the result of a collaboration between Pepperwood scientists, technicians, advisors, and visiting scholars including the Terrestrial Biodiversity Climate Change Collaborative (TBC3; https://www.pepperwoodpreserve.org/tbc3/) co-chaired by Pepperwood and University of California, Berkeley. As a relatively new, long-term ecological research site, Pepperwood complements existing networks including the

international Long Term Ecological Research program of the National Science Foundation (Vanderbilt et al. 2015), the University of California's Natural Reserve System and Agricultural Research Extension centers, Sonoma State University's Center for Environmental Inquiry, California Department of Fish and Wildlife reserves, and other members of the Organization of Biological Field Stations. Pepperwood's Sentinel Site also builds off of regional "Vital Signs" monitoring priorities defined by the North Bay Climate Adaptation Initiative in consultation with the Bay Area Ecosystems Climate Change Consortium and the National Park Service (Micheli and DiPietro 2013) and Pepperwood's Adaptive Management Plan (Gillogly et al. 2017).

This plan aims to define what, where, and how to monitor physical and biological characteristics of the Pepperwood ecosystem (Figure 1). Supporting sections discuss specific methods and approaches to measuring metrics and indicators of climate, hydrology, soils, vegetation, and wildlife. For each of these categories, this report calls out what is currently in place and what we have identified as priority additions targeted over the 2020-2025 period of our current strategic planning efforts.

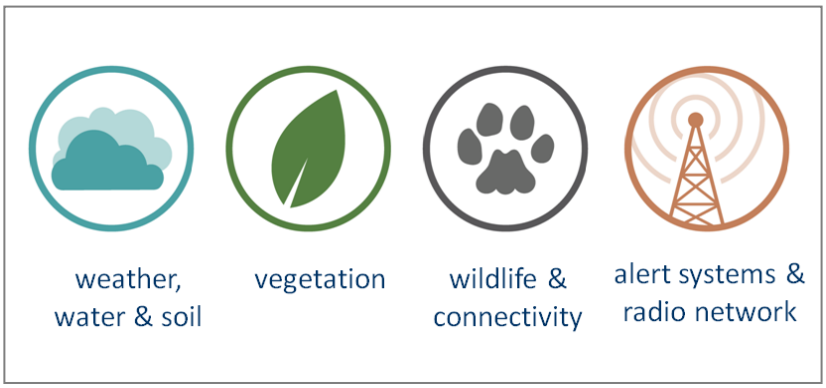

Figure 1: The four major focus areas for Pepperwood's Sentinel Site research.

Here is a summary of key areas of focus. We measure weather (e.g. temperature, precipitation, humidity, and wind) and watershed hydrology (e.g. precipitation, fog, soil moisture, stream flow, groundwater, and springs). We track species composition and other indicators of vegetation health in grasslands, forests, chaparral, and wetlands. We quantify wildlife abundance, behavior, and response to landscape disturbance (e.g. fire, droughts, and floods). These data and information are used to inform on-site research, preserve management, and multi-site assessments and modeling initiatives. Our consistent Sentinel Site monitoring framework provides an excellent foundation for complementary research projects conducted by visiting scholars that are generally shorter-term, hypothesis-focused studies. Our staff scientists plan a critical role as liaisons tying our Visiting Scholar research into the Sentinel Site's longer-term climate and ecological assessments.

In October of 2017, Pepperwood and the Sentinel Site were heavily impacted by the Tubbs Fire that burned 95% of the preserve and consumed the majority of our sensor equipment, communication network, and supporting infrastructure including a barn, vehicles, and staff housing. Post-fire, we have reestablished major components of the Sentinel Site (e.g. wildlife cameras, weather stations) and are currently completing other elements as part of our preserve-wide rebuild (e.g. radio network and distributed soil moisture stations). Several alert systems have been added post-fire in partnership with local emergency response agencies to increase situational awareness during wildfire and flood events. Our experience in 2017 speaks to the value of our Sentinel Site in generating an unprecedented data set of pre- and post-fire conditions in California's Inner Coast Range ecosystems, a data set which is already being put to work to improve climate resilience strategies for our region's private and public agencies. This episode underscores the value of long-term data collection to capture unpredictable events as a critical complement to controlled experimental field studies.

In addition to scientific research, Pepperwood serves as a demonstration site for climate-smart land, water and wildlife habitat management. This adds a dimension of linking Sentinel Site data to land management experiments, and is a critical aid to discerning environmental versus management drivers on landscape attributes. Overlap with our land management research projects is called out in this report as needed for context.

Here, we describe what is in place as of 2019 during the restoration of Pepperwood's Sentinel Site in the wake of the 2017 Northern California fire season, and what equipment or protocols are recommended to be added in the future. This plan serves as a supporting document of the *Pepperwood 2020-2025 Strategic Plan*, funded by the National Science Foundation's Field Station and Marine Laboratories program.

Key Objectives

Field stations like Pepperwood are uniquely poised to fulfill critical roles in scientific research and systematic long-term data collection (Figure 2). Pepperwood's role as a research station is central to its mission. As an independent station supported largely through local philanthropy serving multiple universities and agencies, Pepperwood maintains a laser focus on the collaborative establishment of a long-term Sentinel Site record. Specific Pepperwood Sentinel Site objectives include the following.

1. Conduct research and monitoring that fills scientific knowledge gaps and directly informs natural and cultural resource management at Pepperwood and surrounding areas.
2. Supply local natural resource managers with cutting-edge, accurate, and real-time data on weather and ecosystem health trends and processes.
3. Provide data and expertise to support on-site Visiting Scholar research and expand collaborations to include multiple sites across the state of California and our Western US region.
4. Expand the Sentinel Site concept and methodology to other sites to create Mediterranean ecosystem networks with comparable climate, hydrology, vegetation, and wildlife data and information.

The purpose of this plan is to look forward and proactively define supporting activities central to generating a long-term, high resolution record of climate and ecosystem response in California's Coast Range watersheds. We intend this project to serve as a model for partners who wish to join us in activating a regional, national, and global network of Sentinel Sites.

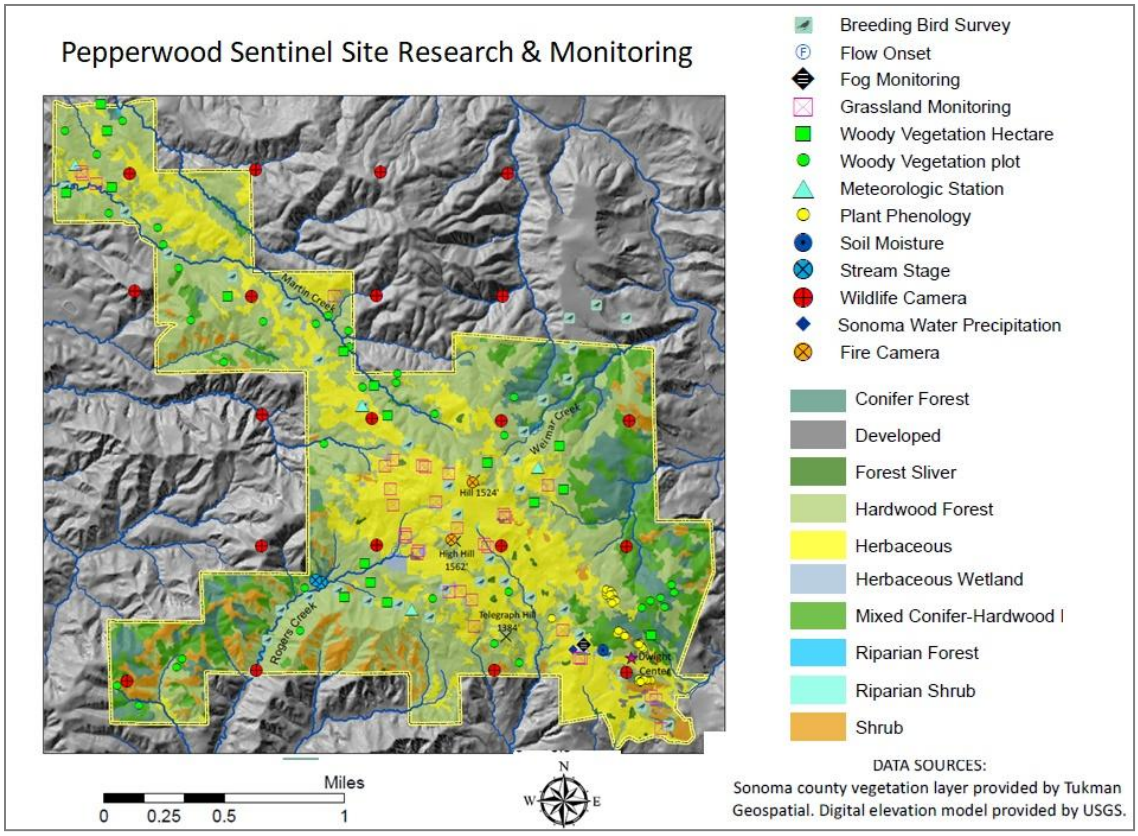

Figure 2: This map shows the distribution of Pepperwood's Sentinel Site monitoring efforts across the preserve. The spatial distribution of sites on the landscape is often stratified by vegetation community as seen on the map.

Research, Inventory, and Monitoring Activities

Climate, Soils, and Hydrology

The aim of the physical monitoring component of our Sentinel Site is to improve our basic understanding of temporally and spatially variable processes driving local climate, atmospheric interactions, and the water cycle across Pepperwood's complex topography. Pepperwood's meteorologic, hydrologic and pedologic monitoring is spatially arranged to capture landscape-level climate gradients driven by orographic and topoclimatic effects on the distribution of energy and water inputs to the system. This design facilitates a more accurate characterization of the heterogeneity of terrestrial "climate space" driven by landscape facets and climate impacts on all elements of the hydrologic cycle. The strategic monitoring of these physical factors through time and space allows Pepperwood researchers and collaborators to assess the interaction of physical factors with complex ecosystem responses such as species distributions and fire risk.

Under the auspices of the TBC3 collaborative, Pepperwood has partnered with the United States Geological Survey (USGS) to serve as a primary research location for development and testing of a fine-scale hydrologic Basin Characterization Model (BCM) (Flint et al. 2012, 2017) that estimates water balance terms based on climate, topography, and geologic structure. BCM output variables include soil moisture, recharge below the soil horizon, runoff, potential and actual evapo-transpiration, and resulting climatic water deficits. Climatic water deficit (CWD) is a measure of the extent to which potential evapotranspiration exceeds actual evapotranspiration, essentially a "drought stress" term.

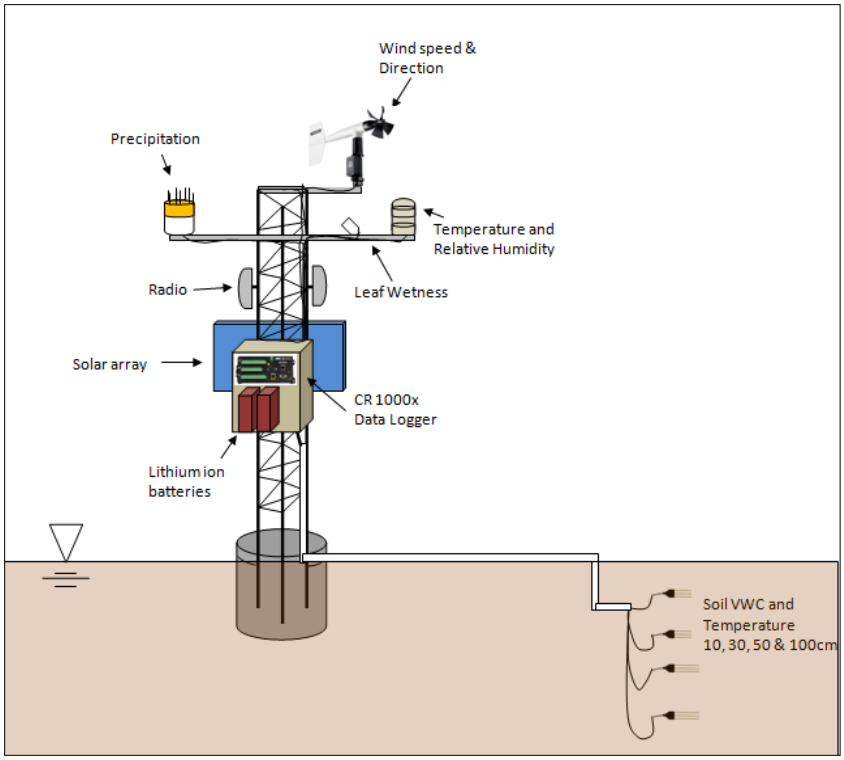

Figure 3: A diagram of one of Pepperwood's five research weather stations.

Climatic water deficit has emerged through the TBC3 research agenda as a critical physical indicator of where different species of vegetation can grow, drought impacts on habitat value and irrigation demand, fuel moisture and resulting fire hazards, and other climatic stressors in our Mediterranean-climate landscape (McLaughlin 2017;Ackerly et. al (in press), Ackerly et al. 2012, Micheli et al 2016). Our physical monitoring thus characterizes different components of the energy and water cycles, and in particular focuses on key processes linking the atmosphere to soils, underlying bedrock deposits, downstream watersheds, streams and wetlands, and local plant and animal communities.

With more than 60% of local precipitation comprised of atmospheric rivers, a subject of active research in partnership with Sonoma Water and Scripps' Center for Western Weather Extremes, our Sentinel Site is poised to complement assessments of atmospheric river formation and transport with the residence time of atmospheric river derived precipitation in our soils, streams and aquifers. Better understanding trends in the delivery and transport pathways of extreme precipitation events, and the relationship to more frequent and intense drought conditions, will be critical to effective climate adaptation in our region.

Weather Stations

Pepperwood's primary weather stations record a standard suite of meteorological data including: precipitation, temperature, relative humidity, barometric pressure, wind speed and direction via two different sensor systems continuously at 15 minute intervals, and at key locations also capture solar radiation, leaf wetness and a suite of soil parameters at four depths down to 91 cm (Table 1 – all tables are in Appendix D). These master stations are complemented by "micro-met" stations installed to complement biological monitoring, as described in more detail below.

Figure 4: Pepperwood's Upper Martin weather station.

Current:

Our current weather station network captures data in each of our five primary drainages to provide a solid framework for documenting watershed-specific long-term conditions. As

of summer 2019, Pepperwood has five Campbell Scientific weather stations and one Davis Instruments Vantage Pro2 station. Pepperwood's Campbell Scientific reference Weather Station was established October 1, 2010 and is referred to as the "Grass" MET station. These full weather stations are sited to capture conditions representative of the five watersheds of the preserve (Figure 3).

The "Grass" MET station survived the 2017 Tubbs fire requiring only moderate repairs and re-calibration. Repairs were also required to restore the Oak Soil Moisture site (Table 2). Four additional weather stations were replaced (Campbell Scientific stations installed in June 2019) at Redwood Pond (Table 3), Roger's Canyon (Table 4), Upper Martin Creek (Figure 4, Table 5), and Lower Martin Creek (Table 6) (see Figure 2 for locations).

Our Campbell weather stations are complemented by an agricultural-grade Davis Instruments Vantage Pro2 weather station located at the Dwight Center for Conservation Science which provides the opportunity to cross-check data and to stream data to Pepperwood's weather website (www.pepperwoodweather.org) using customized software. The Dwight Center station also serves as an educational resource as it sits directly in front of our main building and classrooms.

Proposed:

- Weather stations will be added to this basin-based design as needed to complement future Sentinel Site elements (e.g. flux towers, additional ecological studies, etc.) or monitoring in targeted ecosystems. For example, adding sensors to Pepperwood's serpentine chaparral sites would provide valuable insights into the typically xeric conditions of these unique ecosystems and would provide a supporting baseline dataset for continued research in these locations.

Fog and Atmospheric Deposition

The iconic Pacific coastal fog of our region provides our natural "air conditioning": one of the great uncertainties we face is how fog patterns are responding to a changing climate. Pepperwood's fog monitoring work is informing groundbreaking work on basic physical modeling of controls on fog formation, transport, deposition, and chemical composition at the coastal-inland interface on the part of our visiting scholars.

Current:

In collaboration with researchers from USGS, California State University Monterey Bay, and others, Pepperwood is actively monitoring fog frequency and precipitation with five collectors located at the Bechtel House. The collectors were initially installed in 2014 (replaced in June

2019 due to fire damage). Initiated as part of a regional network, we are quantifying and assessing the spatial distribution of fog to investigate the ecological and landscape level processes that are strongly affected by fog and low clouds along the north and central California Coast (Torregrosa, 2013). The 2019 Pepperwood fog collectors are now connected to our radio communication network allowing for on-demand data access.

Recent fire events across California have highlighted the far reaching effects of fires beyond the burn perimeter. The Bay Area experienced dangerously low air quality levels for several weeks in 2018 due to the Camp Fire. In response, Pepperwood added a "PurpleAir" air quality sensor to join a growing global network of air quality sensors (https://www.purpleair.com/map?#10.09/38.506/-122.5901). This air quality sensor was installed in November 2018 and currently represents the only measurement of air quality on the preserve.

Proposed:

- Install additional fog collectors to measure topographic gradients in fog precipitation frequency, amount and duration. If significant trends were discovered these findings would inform understanding of the speed and velocity of ecosystem shifts in a warming climate. It may be the case that some elevations that typically experience a higher frequency of fog will decrease while others, typically drier elevations, may increase. If this is the case this would have huge ramifications for species dependant on fog (i.e. redwoods, some wine grape varieties).
- Install additional fog collectors to monitor differing sources of fog contribution and track how these sources change over time. Currently Pepperwood experiences fog from two unique source locations: coastal fog coming west to east off of the ocean and bay fog that comes off of San Francisco bay up the Napa Valley and arrives on the southeastern side of Pepperwood. These two sources of fog both cover large agricultural areas that are vital to the local economy.
- Deployment of a third series of fog collectors with partners on the Santa Rosa Valley floor would allow us to more accurately track the inland and elevational extent of fog events and complete a coast to inland transect that now includes collectors located on the coast at the Bodega Marine Lab and inland at Pepperwood. However, during the summer many fog events do not reach Pepperwood and remain confined to the Russian River Valley between the coastal front-range and inner coastal range on which Pepperwood is located.
- Monitor fog water chemistry and isotopic signature to be able to partition out the contribution of fog water to surface, and possibly subsurface, streamflow. This represents an overlapping area of research that links fog precipitation to streamflow.

While these contributions are relatively small they are of critical importance for the survival of anadromous species in these flow limited upper watershed reaches.

- Throughfall experiments under canopy to relate the amount of fog we are measuring with our collectors to biologically accessible precipitation. Canopy throughfall experiments would allow us to measure how much fog precipitation is actually reaching the forest floor. Stratifying by different canopy types and densities it may be possible to extrapolate fog contributions at a regional scale. These contributions are critical, particularly in late-summer, fire-prone landscapes of Sonoma County where fog represents one of the few offsetting factors to low fuel moistures and high water stress. We propose expanding an ongoing fog particle size analysis program using an FM 120 Fog Monitor. Fog particle size analysis will allow us to determine trends in fog particle size seasonally, annually and in response to climate change. We would be able to link these measurements to changes in other physical factors including temperature, wind patterns and solar radiation. Furthermore, this analysis will elucidate the relationship between capture rate and particle size for each mesh type. If we see significant results in this and we see a trend developing in particle size through time we can inform what fog collection mesh material to use in the future.
- Install flux towers to monitor the fluxes of energy and gases in grasslands and above canopy in deciduous oak forests. These assemblages represent two of the most abundant vegetation communities across the preserve. Flux data for CO2 and water vapor can then be used to estimate rates and amounts of evapotranspiration (ET). Further modeling efforts may be able to link remotely sensed measurements of Normalized Difference Vegetation Index (NDVI) to ET allowing for a rapid extrapolation of ET to watershed scales (Goulden et al. 2012). This will further constrain the uncertainties in our local water balances and help to elucidate the biological controls on streamflow and soil moisture.
- Atmospheric nitrogen deposition is a profound change in the environment that has cascading effects through ecosystems, because nitrogen is a key limiting nutrient. Grasslands, in particular, are highly sensitive because nonnative grasses respond so strongly to added N (Fenn et al. 2010). The Mayacamas mountains are predicted to have relatively high nitrogen deposition (7-20+ kg-N ha^{-1} yr^{-1}) based on CA Energy Commission models (Tonnesen et al., 2007, Fenn et al. 2010) and National Atmospheric Deposition Program (NADP) Total Deposition maps (https://nadp.slh.wisc.edu/committees/tdep/tdepmaps/), because they are downwind of the urban and agricultural sources on the Santa Rosa Plain and Petaluma Gap. Levels and trends in nitrogen deposition will be measured with passive samplers and ion exchange resin beads. Passive samplers measure time-averaged atmospheric concentrations of major nitrogen species (NO_x, NO_2, NH_3, and HNO_3) on a monthly basis.

Ion exchange resin beads measure N in throughfall (including fog drip) and bulk deposition. A network extending from the Santa Rosa Plain through Pepperwood and into cleaner air regions beyond will be powerful documentation of N-deposition in Sonoma County.

- Expand air quality monitoring locations to capture topoclimate gradients across the preserve. Sonoma County is prone to wintertime inversion layers that significantly reduce regional air quality. Pepperwood's elevational gradients provide the opportunity to monitor where and when these inversions occur and to measure the resulting reduced air quality. This dataset is of significant importance as it would inform risk to human health.
- Utilize Pepperwood's weather station network to help characterize "fire weather" conditions to inform improved hazard reporting and capture fire event air quality impacts locally (the Tubbs Fire corridor) and regionally (Northern California).
- Partner with visiting scholars seeking high resolution atmospheric data to inform near-surface meteorological fire behavior and potential fire spread models.

Soil Properties and Nutrient Cycling

Soils provide the living medium for water and energy exchange at the interface between the atmosphere and the earth. The soils of Pepperwood are reflective of the highly diverse and tectonically active geologies of the Coastal Range of California. Characterizing, mapping and understanding the myriad of soil types and their properties across the preserve is of critical importance. Currently there are 15 mapped soil series across the preserve ranging in texture from clay loams to rocky loams (McLaughlin, 2005). Pepperwood also features nearly 100 acres of serpentine soils that host specialized, rare and endemic plant communities.

We have yet to complete comprehensive profile characterizations of soils at Pepperwood beyond data gathered in the course of soil moisture instrumentation (see below). Current soil monitoring efforts across Pepperwood have been largely aimed at understanding the impacts of grazing and fire on soil properties including carbon storage, infiltration, and bulk density.

Current:

In December 2016, Pepperwood completed a first round of soil measurements for soil organic carbon and bulk density following Point Blue protocols (Porzig et al. 2018). These measurements were co-located with five transects in our grassland monitoring project to examine the effects of grazing on near surface soil properties. We are actively partnering with visiting scholar specialists in this area to determine how to augment our long-term carbon cycle monitoring efforts.

Pepperwood is currently collaborating with USGS on a regional project to investigate fire impacts on hydrophobicity, soil infiltration rate recovery, and sedimentation rates following the October 2017 Tubbs Fire. Continued soil research is needed to help better quantify the full hydrologic cycle, carbon and other nutrient cycling, and impacts of management; and to help elucidate the controls soil properties are exerting on biologic and hydrologic responses in the ecosystem. Augmenting the monitoring of soil carbon in concert with a full carbon cycle assessment (including proposed flux towers above) is a key focus area for Sentinel Site expansion.

Proposed:

- Continue and expand soil infiltration measurements. As a way to quantify the impacts of our management practices we propose conducting pre- and post-management measurements of soil infiltration and continuing these measurements through time as necessary to fully capture the long-term impacts. These measurements will be particularly important in estimating and validating models of recharge and runoff. Furthermore, this data may be useful for regional flood forecasting models.
- Conduct full profile characterizations of the dominant soil types at Pepperwood. This would require pit excavations down to consolidated bedrock where feasible. In addition to the in-field taxonomic classification and characterization, further laboratory analysis would be conducted, by horizon, to measure: bulk density, porosity, saturated hydraulic conductivity, cation exchange capacity (of pertinent horizons), particle size, and to develop soil water retention curves. Many of these soil properties are relatively static through pertinent timescales which means this would be a one-time campaign to document the characteristic properties of these soils.
- Apply seismic soil profiling tools to characterize below-ground structure of soils and underlying weathered bedrock to complement pit excavation and provide for spatial extrapolation.
- Construct a landform map and sediment budget with additional sediment monitoring tools (surface runoff, soil creep indicators, ground and remote-based mass wasting indicators, suspended sediment)
- Develop a paired monitoring scheme examining surface horizon changes in bulk density, soil organic carbon and nitrogen content between grazed and ungrazed plots. This would provide valuable insight into the long-term effects of grazing and would help to inform best management practices to preserve beneficial soil functions.

Soil Moisture

In a Mediterranean climate, soils form a critical repository for water storage that local plants and many animals rely upon to survive the summer season. Soil moisture dynamics in our region also serve as a control on human water demand and supply in aquifers, streams and rivers, and artificial reservoirs. Soil moisture measurements are a critical component of understanding the water cycle at Pepperwood and across the Inner Coast Range. Understanding impacts of climate change on soil moisture is therefore crucial to informing climate adaptation strategies for our region.

Pepperwood's soil moisture data is used to calibrate a USGS water balance model called the Basin Characterization Model (BCM) (http://climate.calcommons.org/bcm) that provides historical and projected climate and hydrology data at a relevant resolution for watershed-scale evaluation and planning (Flint and Flint 2012). Data from the Pepperwood weather-soil moisture array has also been used to evaluate drought impacts on forests (McIntyre et al. 2015) and recovery trajectories of local Sonoma Water supply reservoirs during the historic 2011-2016 California drought. Studies presently underway with the USGS are using this dataset to inform field based assessments of 2017 fire impacts and potential forest management effects on soil moisture dynamics.

Current:

Measurements of soil variables are co-located with our five Campbell Scientific weather stations and one additional site referred to as the "Oak" soil moisture station, installed in July 2011 (Table 2). The Grass and Oak Campbell stations have paired sensors at four depths each that record soil water content, temperature and matric potential. The Grass station has paired sensors at depths of 15, 30, 56 and 91 cm, and the Oak station sensors are located at 5, 20, 46 and 66 cm due to soil depth limitations. These two stations were originally installed in partnership with Drs. Lorraine and Alan Flint and Mike Andersen (USGS) as part of an experimental design. Pepperwood assumed full responsibility for this equipment in August 2017 as part of the long-term Sentinel Site. The weather stations in Redwood Pond, Upper Martin Creek, Lower Martin Creek, and Rogers Canyon now also measure soil water content, temperature and electrical conductivity at 15, 30, 50 and 100 cm.

Proposed:

- As part of the Sentinel Site post-fire recovery, Pepperwood is in the process of installing 17 smaller scale meteorological and soil monitoring stations that measure temperature, relative humidity, leaf wetness and soil moisture, temperature and electric conductivity at 15, 30 and 50 cm (Table 7). These stations are co-located with NSF-funded long-term woody vegetation research sites (Dr. David Ackerly, University of California Berkeley).

- As we expand our fire science research and collaborations, we will add to our extensive soil moisture sensor network to inform near real-time fuel moisture monitoring. Expansions of our soil moisture monitoring will be co-located with measurements of live fuel moisture to develop a better understanding of the drivers of fire risk.
- Add soil monitoring in targeted ecosystems such as grassland and serpentine chaparral to provide baseline data for continued research in these communities.
- Compare field-based soil moisture assessments to remotely measured indicators on next-generation satellites, such as NDVI, ground penetrating radar.
- Augment soil moisture probes with deeper neutron tube probes to capture interactions with fractured bedrock water deposits.
- Please see Vegetation section below for more details on pairing of soil moisture assessments with long-term vegetation monitoring.

Springs, Ponds, and Groundwater

From late summer through early fall (prior to any rains), surface flow in and below stream channels at Pepperwood is solely generated by springs. This is typical of the inner California Coast Ranges, where many streams are intermittent (e.g. dry out during the extended summer conditions). This extended and sometimes perennial spring production of water provides important insights about the complex subsurface hydrodynamics of faulted and fractured bedrock hill slopes. The spatially-variable emergence of springs at the ground's surface drives the occurrence of cooler, wetter habitats that are locally rare and significant to many at-risk species. These "hydrorefugia" are recognized as sources of resilience in a landscape projected to become progressively more arid (Mclaughlin et al. 2017, Scholl et al. 2014).

Current Springs:

In the summer of 2016, the TBC3 team investigated a number of "developed" springs (hardware had been added for water collection purposes), to explore approaches to measuring spring flow over time. The Bechtel box spring was identified as offering perhaps the best opportunity for mechanical monitoring, with all flow routed through a single pipe. While the group discussed potential stilling basin designs, an in-pipe meter seemed most promising. However pilot tests showed that the meters were not accurate in an unpressurized pipe where discontinuous flow is common. In August of 2017, to support monitoring objectives, a comprehensive spring characterization was conducted of 40 springs and seeps across the preserve. The purpose was to create an accurate location map, assess physical and biotic site characteristics, and where feasible, obtain single point in time observations of flow using a bucket and stopwatch method.

Current Ponds:

A citizen science pond monitoring project took place at Pepperwood's Turtle Pond from fall 2011 through winter 2017. Physical pond metrics of size and depth as well as water quality metrics including pH, alkalinity, water hardness, turbidity, nitrate concentration and water temperature were recorded approximately every two weeks throughout this period. These data may ultimately serve as a baseline for future studies examining biologic and hydrologic functions of these upper watershed pond ecosystems. Pepperwood's ponds serve as a vital seasonal habitat for reptiles and amphibians and serve as an indicator of ecosystem health.

Current Groundwater:

Pepperwood maintains a public water system to support its facilities, which is supplied by a well that was constructed in 2009. This production well has been monitoring to measure the elevation of the local groundwater table since 2010. As of August 2017, water depth is now documented monthly at our primary production well, the well at Hill 1524 (used for cattle), and the well at Garrison Canyon (residential use). Quarterly records of depth to water and water usage are reported to Sonoma County. Our experience during the recent drought demonstrated that groundwater measurements provide an early warning if the water table elevation is dipping below production pumps. Ultimately, our goal is to have a record to inform our understanding of fractured bedrock hydrology typical of the Inner Coast Ranges.

Proposed Springs:

- Implement spring flow monitoring. For the 2019-2020 water year, we will make monthly to bi-weekly bucket and stopwatch flow measurements to get a first order estimate of flow variability relative to rainfall, soil moisture, and stream flow time series. We will concurrently examine sensor-based options and engage experts to design a sampling protocol.

Proposed Ponds:

- Instrument Pepperwood ponds with a comprehensive suite of sensors to track patterns in the localized microclimates. Additional sensors would capture the hydrologic conditions of these systems including water depth, temperature, pH, dissolved oxygen and turbidity.
- Collect and analyze monthly water quality samples to track changes in the concentration of specific compounds including nitrates [NO3-].

Proposed Groundwater:

- Install a series of neutron probe access wells in order to measure deep groundwater, and to better characterize the soil moisture conditions at depths that correspond to

summer utilization by Mediterranean ecosystems. This will represent a rare look into the deep subsurface properties that support our forests. Most soil moisture measurements are limited to the upper meter of soil. However, neutron probe wells, where possible, are installed into the deeper fractured bedrock matrix. These wells will be set up in paired installments representing North versus South aspects and differing geologies. This installation pattern will shed light on the lithologic controls on subsurface hydrology and will help inform how species may shift in a warming, drying climate as predicted by some current models.

Stream Monitoring

Pepperwood's watersheds provide approximately 30,000 acre-feet per year of water to downstream portions of the Russian River watershed, which as a whole provides drinking water for 600,000 people. Resources downstream include the RAMSAR recognized Laguna de Santa Rosa wetland and drinking water aquifers of the Santa Rosa plain supplying Sonoma County's capital city of Santa Rosa, and nearby Rohnert Park, home to Sonoma State University. Streamflow measured at Pepperwood provides critical data on headwater contributions to downstream flows supporting endangered species habitat and human water supplies; the hydrograph for unimpaired flows; and a critical term for closing water balance assessments with empirical data. Local water agencies, including Sonoma Water, have used Pepperwood's data to inform water supply, flood risk, and in-stream and riparian habitat assessments.

Current:

Stream stage and temperature are measured by a paired set of pressure transducers on Rogers Creek. While most of the creeks on Pepperwood are extremely ephemeral headwater channels and wet mainly during rainfall events, this bedrock/coarse alluvial reach of Rogers Creek generally has at least wet pools year round. Rogers Creek is also a tributary of Mark West Creek, a critical flow-limited Coho salmon habitat. The Rogers Creek drainage monitored by Pepperwood (drainage area = 247.35 acres, elevation = 228 m) provides an important Coast Range reference site, as there is no water supply development (diversions or streamside wells) upstream. However, the steep step-pool channel morphology (reflective of high energy and high coarse sediment transport–including large cobbles, small boulders, and gravel pulses–during floods) and extremely low summer base-flow typical of this reach introduces challenges to accurate monitoring. The redundant pairing of sensors at this location is a preventative measure to guard against loss of the data record due to burial by sediment during high flow events.

Velocity measurements needed to develop a stage-discharge curve are challenging to obtain on dynamic channel morphology and for safety reasons. Despite these obstacles we have

completed several rounds of stream velocity and wetted channel area measurements at different stage heights to begin to develop an approximate rating curve. While our measurements of discharge remain uncertain we do continue to record and maintain an ongoing record of stage and temperature for this location. These data provide a critical baseline, particularly for cold-water fishery habitat evaluations, and provides a basis for first order estimates of cumulative runoff during storm events or on an annual basis.

Flow onset is currently recorded in three of the five watersheds emanating from Pepperwood. These watersheds include Rogers Creek, Martin Creek and Lower Franz Creek. The catchments corresponding to these measurements range in contributing area from 50-69 acres and represent the upper most headwaters of these systems. Flow onset is approximately determined, based on the relative difference in temperature between the stream bank and the lowest point in the stream channel (where we anticipate the initiation of flow). When there is no flow both sensors show a strong diurnal cycle and similar temperature. Once flow occurs, the in-channel sensor has a muted diurnal pattern resulting in reduced high temperatures and elevated low temperatures due to the high specific heat of water. As previously mentioned, this measurement is very approximate. This uncertainty stems from the rapid event-driven onset of flow where flow can begin and end in just a matter of hours. Additionally, event-driven changes in streambed morphology will result in the fixed sensor location no longer corresponding to the deepest part of the stream channel. Future implementation to capture surface hydrology will attempt to reduce the uncertainty in both discharge and flow onset by introducing better infrastructure to constrain flow to measurable geometries.

Proposed:

- Install gauging on each stream with communications capacity. Regional and statewide hydrologic-based modeling efforts rely heavily on accurate measurements of flow. Additionally, from a water balance standpoint surface flow is an essential measurement needed to close the water budget.
    - Install fixed geometry weirs or flumes from which to calculate accurate measurements of stream flow.
    - Retrieve these measurements in real time by connecting to one of two radio networks currently deployed on the preserve.
    - Develop rapid data dissemination procedures in collaboration with Sonoma Water to help further refine their flood risk evaluations.

Figure 5: A fixed geometry weir (left) and flume (right) that are representative of the proposed methods for gauging flow from Pepperwood's smaller headwater catchment areas.

- Measure flow onset in all five of Pepperwoods watersheds. Additionally, Pepperwood is criss-crossed by a multitude of transverse faults that have resulted in a heterogeneous landscape of differing geologies and soils. This heterogeneity imparts unique hydrologic patterns to each of Pepperwood's watersheds. These patterns in hydrology are temporally and spatially unique with flow sometimes moving back and forth through the hyporheic zone. To capture this heterogeneity we propose instrumenting the stream channels with flow onset sensors in a longitudinal array moving up the stream channel. This would allow us to delineate reaches of surface and subsurface dominated flow.
- Monitor hyporheic zones to capture full surface water flux. The persistence of pools in some reaches throughout the summer months suggest that subsurface flow in the hyporheic zone is sustaining these pools. Subsurface flow is an important flux in the water balance but remains difficult to measure.
    - We propose installing paired transects of piezometers perpendicular to the stream channel. Where possible, piezometers will be installed in consolidated hard bedrock, which acts to constrain the flow. By pairing these transects (one upstream and one downstream) we can measure the hydraulic gradient between the wells.
    - Further, analysis will be needed to determine the saturated and unsaturated hydraulic conductivity of the channel bed materials.

    - Approximate the flux between wells and develop estimates of subsurface flow to further refine our understanding of the regional water balance
- Track stream water chemistry through time. This data record will be of critical importance for understanding how nutrients move through the ecosystem and where they come from. Emerging techniques also allow use of water chemistry signatures to inform estimate of water residence time ("age") and transport paths.
- Pepperwood currently grazes about 150 head of cattle in different regions of the preserve throughout the year. The effect this management has on our stream water quality has yet to be quantified. These data will allow pepperwood to:
    - Quantify the impacts of grazing practices on nutrient loading to surface waters.
    - Measure seasonal trends in water chemistry as the ecosystem transitions through different phenological phases that impact the magnitude of nutrient uptake by vegetation.
    - Quantify how prescribed fire affects both stream flow and nutrient loading of the streams.
- Track sediment transport via addition of suspended sediment/turbidity sensors at gauges and indicators of bed load transport via repeat topographic surveys (field based and potentially remote).

Vegetation

Formal documentation of vegetation diversity at Pepperwood was initiated with the California Academy of Sciences in the 1980s when resident biologists collected herbarium specimens and developed the Pepperwood Vascular Flora (DeNevers 2013). Since launching the Sentinel Site in 2010, Pepperwood has ramped up monitoring of our abundant and diverse preserve across three main vegetation types: grasslands, forests, and chaparral. As a result, we are gaining a better understanding of what drives plant species distributions and abundances, survival and growth rates, life cycles and phenology, reproductive success, community dynamics, and responses to our land management. Given recent trends toward warmer and drier conditions, we can observe how plant species, their communities, and habitat structure, are all shaped by the changing climate. By monitoring species' responses to the October 2017 Tubbs Fire we can assess how ecosystem recovery may affect future fire risk and behavior. As vegetation influences wildlife habitat and food webs, we can examine how, when and where wildlife utilize the varied habitats of Pepperwood, and how that behavior may change relative to weather or shifts in habitat condition. In turn, by documenting these processes we can assess our management impacts and decision-making strategies, and test whether we are achieving our habitat management objectives.

Stephen J. Barnhart Herbarium

The Stephen J. Barnhart Herbarium at Pepperwood was formally established in 2012 in honor of our Founding Academic Director and was listed in the International Herbarorium in 2018. The Barnhart Herbarium is managed by Pepperwood, but primarily fueled and curated by volunteers. The Pepperwood Vascular Flora (DeNevers 2013) is updated on an annual basis, regularly adding new species, subspecies and varieties to our record.

Current:

The Barnhart Herbarium houses the only formal biological collection at Pepperwood and includes specimens of vascular plants, lichens and fungi collected from the preserve and the immediate environs since the 1980s. These specimens are not only a physical record, but a genetic record of the botanical diversity at the preserve. Many of the specimens are duplicates from the California Academy of Sciences, serving as an important redundant record in the event of a catastrophic emergency that could destroy physical records such as fire, flooding, or earthquake. In an age where botanical collections are continually at risk of being lost forever, the importance of small herbaria to sustain and support botanical, genetic, and phenological records has never been more evident.

Proposed:

- Upload digital specimen records to the California Consortium of Herbaria so that our collection becomes searchable and available to the public.
- Expand collection efforts to include revisiting sites that (1) historically had rare or uncommon species to the preserve, and (2) are areas with limited sampling.
- Expand collection efforts to include fungal, lichen and moss (or other bryophyte) taxa.
- Enhance strategic sampling efforts. For example, expand where and when collections are conducted to incorporate more of the spatial and temporal variation on the preserve. Another option would be to strategically sample areas, communities, and/or species that may be climate-sensitive.
- Consider dedicating additional resources to the herbarium and hiring a formal herbarium manager.
- Consider conducting seed bank collections when making herbarium specimen collections for rare taxa. Deposit seed stock to an accredited bank (e.g. Santa Ana Botanical Garden) where they may be preserved and remain accessible for future research and restoration projects.

Phenology

Phenology (the study of plant and animal life cycle and behavioral timing) is finely tuned to the weather, and a well-suited focus of climate-ecosystem investigations. Starting in 2013, citizen scientists at Pepperwood have been tracking the effects of climate on California native plant life cycles through the National Phenology Network and the California Phenology Project, under which Pepperwood is considered a Local Phenology Leader

Current:
From 2013-2017, Pepperwood volunteers monitored individual plants, representing 11 species of woody shrubs and trees, along multiple transects twice a week throughout the year. As of October 2017, right before the Tubbs Fire, we had collected over 80,750 plant phenology observations.

All plants monitored in this project were affected by the Tubbs Fire and many were completely killed or consumed. Given that there is no post-fire phenology protocol, and multiple California phenology sites have burned in recent years (e.g. Hopland Research and Extension Center in July 2018), Pepperwood staff and citizen scientists have modified the project to monitor plant recovery and the rate at which each species returns to a "normal" climate-driven phenological state, versus a state of growth associated with fire disturbance.

In November 2017 we were able to recommence data collection on multiple oak species that were not heavily impacted by the fire. In February 2018 we began revisiting plants that were greatly impacted by the fire to monitor their post-fire recovery (e.g. mortality, leaf scorch and canopy damage, basal sprout counts and heights, etc.) and phenology on a regular basis. In March 2018 we established a new transect in an area with little fire impact to supplement the phenology plants consumed and killed by the Tubbs Fire. We are currently analyzing the data to develop monitoring recommendations and will be presenting our findings to the National Phenology Network, with the goal of advising other monitoring sites that experience fire.

Additional active projects that monitor phenology include Pepperwood's annual grassland monitoring (capturing phenological shifts during the weeks of May 1-15 each year) and Pepperwood's annual breeding bird survey (capturing phenological shifts in breeding bird behavior every April-June).

Proposed:

- Expand phenological monitoring to pond and aquatic systems, including monitoring the emergence timing and demographics of the threatened western pond turtle (*Actinemys marmorata*) (see Wildlife and Connectivity - Reptiles and Amphibians section below).

- Expand phenological monitoring to incorporate critical food web species.
- Expand phenological monitoring to incorporate plant species that may be particularly sensitive to climate change (e.g. cool-adapted species such as Oregon oak (*Quercus garryana*)) and/or interannual climate variability (e.g. herbaceous species).
- Expand phenological monitoring to include invertebrates (e.g. butterflies and moths), documenting emergence timing and species diversity and abundance (see Wildlife and Connectivity - Invertebrates section below).
- Expand bird surveys into fall and winter months to capture overwintering and migratory behavior patterns (see Wildlife and Connectivity - Birds section below).
- Compare field phenology indicators with remote-sensing data indicators.

Fuel Moisture

Located in the heart of a known fire corridor, Pepperwood is ideally situated to monitor fuel moisture conditions of both dead and living materials. High frequency monitoring is most critical throughout California's expanding fire season, typically summer through fall prior to any significant precipitation events. Moisture levels in soils and vegetation reach critically low levels in early fall and are prone to catastrophic wildfire. Live fuel moisture is the common metric used in determining daily fire risk--an indicator that recent TBC3 research suggests is closely correlated with soil moisture and climatic water deficits.

Current:
In June 2019, we established a live fuel moisture monitoring protocol for three unique vegetation communities across the preserve including chaparral, and mixed hardwood and Douglas-fir forests.

Additionally, we are monitoring 10-hour dead fuel moisture and air temperature along a northwest facing elevational transect at two locations. These data are a 15-minute real time data stream that, accessible through our radio network. We would like to expand our monitoring efforts to better inform fire risk modeling and our own management activities on the preserve.

Proposed:
- Paired soil moisture sensors in live fuel moisture monitoring plots. These co-located data streams represent a critical linkage for modeling efforts seeking to elucidate landscape level relationships between soil moisture and live fuel moisture.

- Expand our network of 10-hour dead fuel moisture to other regions of the preserve. This will involve adding sensor to current meteorological stations that are stratified across topography and climatic gradients.
- Expand our network of wind anemometers to key locations on the preserve to better understand seasonal wind patterns that can exacerbate fire severity. This may also shed light on how topography shapes, accelerates and funnels wind through the landscape giving rise to high frequency fire corridors.

Grasslands

Over 900 acres, representing about one-third of Pepperwood's footprint, is designated as grassland. This vegetation type undergoes the most intensive management and restoration at the preserve given that grasslands are the most invaded plant community and that they require disturbance in order to remain grasslands and avoid succession into shrubland or forests

Current:
Since 2011, Pepperwood has monitored grassland ecosystem health on an annual basis during the calendar dates of May 1-15. This study has allowed us to document, measure, and quantify grassland community and species composition, diversity, and productivity; cover of thatch, bare ground and disturbance; annual variation of fresh material and thatch biomass; assess the impacts of our grazing operations such as the effect of stocking rate, seasonal timing, and rest from grazing on grassland dynamics, diversity and health; and modify our grassland management directly based on our observations and findings.

Over the course of the annual grassland monitoring project we have (1) increased our sampling transects from 25 to 32 locations, (2) modified transect locations to represent the range of climatic conditions across Pepperwood's grasslands using cutting-edge downscaled climate models that were generated by TBC3, (3) collected soil infiltration and soil properties data at 8 transect sites using Point Blue's rangeland monitoring protocols (Porzig et al. 2018), (4) installed 7 new paired transects in spring 2017 that have permanent exclusionary fencing to enable us to tease apart climate versus grazing impacts to our coastal grassland communities, (5) monitored post-Tubbs Fire first order effects 3-4 weeks following the 2017 Tubbs Fire, and (6) began monitoring soil moisture in spring 2019 along transects at the time of sampling to document how soil moisture may influence species distributions and community dynamics.

In 2019, Pepperwood was awarded funding from the California Department of Fish and Wildlife (CDFW) to implement and monitor post-fire restoration and land management activities. A large component of the grant funds the development and implementation of a prescribed

burning plan in grasslands, as well as conducting restoration and management activities (i.e. conservation grazing), providing the opportunity to expand our research of grassland response to climate and management.

Proposed:

- Develop a rigorous grassland soil assessment and monitoring project.
    - Document rates of wet-up and dry-down (e.g. collect measurements of soil moisture along grassland transects throughout the year using a Hydrosense wand).
    - Expand the soil moisture assessment to include large ring infiltrometer measurements each spring and to incorporate more transect locations.
    - Document potential changes to soil properties and biota given our land management (e.g. carbon sequestration, compaction (penetrometer), chemistry, microbial and fungal communities).
- Expand our research impact by establishing multi-site collaborations, prioritizing sites that also have grazing and fire history.
- Expand our research team to include data analysts and grassland ecology experts.
- Complete a comprehensive data analysis on our 8-season annual grassland monitoring dataset in collaboration with the University of California, Davis. We will conduct power analyses on our annual grassland monitoring dataset to determine (1) if the current sampling design is adequate to address questions relating to long-term climate change effects; and (2) if the 7 paired excluded transects adequately capture the variability represented across the preserve and within our management activities so we can address the question of climate versus grazing impacts. We will develop a standardized data analysis toolkit (e.g. in R) that can be updated annually to generate a "grassland health report card" that will inform our adaptive management program.
- Consider experiments testing impacts of different prescribed fire and grazing regimes on grassland health, especially within cool-adapted coastal grassland communities that may be climate-sensitive.
    - Establish an experiment testing the effects of late spring versus fall prescribed fire on native perennial coastal grass species (e.g. CA oatgrass (*Danthonia californica*) which has been observed to be negatively impacted by late spring burning).
- Consider participating in the Drought-Net Research Coordination Network to look experimentally at impacts of climate change on coastal California rangelands.
- Identify critical data gaps and potential experiments to inform grassland invasive species management.

- Install flux towers to monitor the fluxes of energy and gases in grasslands and above canopy in deciduous oak forests. These assemblages represent two of the most abundant vegetation communities across the preserve. Flux data for CO2 and water vapor can then be used to estimate rates and amounts of evapotranspiration (ET). Further modeling efforts may be able to link remotely sensed measurements of NDVI to ET allowing for a rapid extrapolation of ET to watershed scales (Goulden et al. 2012). This will further constrain the uncertainties in our local water balances and help to elucidate the biological controls on stream flow and soil moisture.
- Consider monitoring atmospheric nitrogen deposition in nutrient-depleted and endemically rich serpentine grassland communities. Document potential shifts in species composition, abundances, and growth rates.

Forests

About two-thirds of Pepperwood is composed of diverse forest and woodland communities such as Douglas-fir forest (361 acres, 12% of land mass), mixed hardwood forest (637 acres, 20%), oak woodland (947 acres, 30%), and Pacific coast redwood forest (13 acres, <1%). Many of these forests have a dense understory of sapling trees including California bay laurel (*Umellularia californica*), madrone (*Arbutus menziesii*) and tanoak (*Notholithocarpus densiflorus* var. *densiflorus*). In some areas manzanita (*Arctostaphylos* spp.) or chamise (*Adenostoma fasciculatum* var. *fasciculatum*) are found dead or struggling to survive beneath the shaded overstory, providing evidence of succession in these forests.

In October 2017, the Tubbs Fire burned 95% of the preserve, the majority of which was a surface level burn that cleared away built up debris and litter on the forest floor. However, some areas of the preserve were burned with high severity, top killing entire stands of trees and restarting the successional cycle. Pepperwood's long-term forest monitoring program (described below) is providing critical insight into the post-fire recovery of Coastal forest and woodland communities, informing forest management strategies in California.

Current:

Pepperwood's woodland and forest communities containing mixed hardwood and Douglas-fir are being monitored through UC Berkeley's long-term forest research program (Ackerly et al. 2013). The Sentinel Site currently includes 54 long-term forest monitoring plots in partnership with Dr. David Ackerly and with funding from the National Science Foundation. These plots are designed to test the role of topoclimate diversity in driving species composition and change over time (Oldfather et al. 2016). Located across the preserve to capture variability in topoclimate, plots are instrumented with climate and hydrology sensors and are excluded from management activities (e.g. forest thinning, prescribed fire and grazing). Post-Tubbs Fire, these

plots provide an unprecedented opportunity to evaluate impacts of fire and recovery of montane hardwood ecosystems.

In 2019, Pepperwood was awarded funding from the CDFW to implement and monitor post-fire restoration and land management activities. A large component of the grant funds the development of a forest fuels management and monitoring program, providing the opportunity to expand our long-term monitoring plot network into the managed forest landscape, and enabling us to document pre- and post-thinning ecosystem response in a changing climate.

Proposed:

- Establish an integrated forest monitoring network in areas that will undergo forest thinning in the next five years (co-locate climate and wildlife sensors and monitoring) (CDFW grant opportunity).
- Use ground based LiDAR to measure above ground ladder fuels and carbon pre-/post-thinning (collaboration with Sonoma State University).
- Monitor forested areas that are considered climate-sensitive, such as north-facing cool-adapted communities that are projected to decline under climate change, to document community shifts and the drivers of change over time.
- Consider conducting seed bank studies to see if species that are drought resistant are present in the soil in these climate-sensitive locations/communities.
- Consider conducting experimental common gardens with genotypes from drought-resistant communities/locations in these climate-sensitive communities/locations.
- Consider monitoring forest disease dynamics such as sudden oak death, fungal pathogens, and fire-following wood borers, bark beetles and other pests.

Chaparral

Pepperwood hosts approximately 215 acres of chaparral vegetation, which amounts to about 7% of the land, speckled throughout the preserve in a mosaic with forested and woodland areas. In a few areas, chaparral is composed of nearly pure stands of 8 to 15-foot-tall manzanita. In other areas the cover is a mix of manzanita, chamise, buck-brush (*Ceanothus cuneatus* var. *cuneatus*), and sticky monkeyflower (*Mimulus aurantiacus* var. *aurantiacus*). Pepperwood also harbors serpentine chaparral - a type of chaparral that is specially adapted to the geochemical qualities of serpentine soils including the endemic shrub leather oak (*Quercus durata* var. *durata*).

All chaparral at the preserve burned in the October 2017 Tubbs Fire. Areas once dense with shrub cover, impassable by humans, are now wide open and dominated by ephemeral fire-following wildflowers, grasses and low-lying regenerating shrubs. Pepperwood's chaparral

monitoring program (described below) is providing critical insight into post-fire recovery of chaparral communities, informing natural land management strategies in California.

Current:
Pepperwood is working with Nomad Ecology to capture successional vegetation dynamics of the post-fire chaparral flora in the 2017 Tubbs Fire perimeter (field data collected in 2018 and 2019). We are monitoring 10 chaparral transects (stratified across soil types) to assess the suite of annual and perennial species that benefit from, and/or rely on fire as a part of their life history cycle. Species richness and ecological dynamics are not well understood in these post-fire floras (especially in northern California) despite high interest from land managers, ecologists, and botanists. Additionally, our citizen scientists are documenting the phenology of multiple shrub and tree species growing in serpentine chaparral. Due to the difficult nature of working in chaparral, post-fire conditions pose a unique opportunity to document vegetation composition and identify locations with temporally, and sometimes spatially, rare species.

Proposed:

- Evaluate the feasibility of using remote sensing tools to track chaparral recovery to fire and response to climate change.
- Expand weather and wildlife sensors and surveys to easily-accessible chaparral locations to capture physical and biotic changes over time.
- Map rare and uncommon species' distributions within chaparral before canopy closure (i.e. within the next 3 years).

Wildlife and Connectivity

A critical knowledge gap regarding Northern California's wild and working lands is the general absence of any consistent, long-term quantitative data on wildlife populations. At Pepperwood, we track wildlife occurrences, behavior, and response to landscape disturbances to better manage wildlife on the preserve and to help guide the identification and protection of wildlife corridors throughout the region and state.

Mammals

Current:

In 2010, Pepperwood piloted the use of motion-detecting wildlife cameras with a group of dedicated citizen scientists. This effort allowed us to test the utility of wildlife camera traps (primarily capturing mammals) and build expertise in camera deployment prior to developing a long-term monitoring protocol.

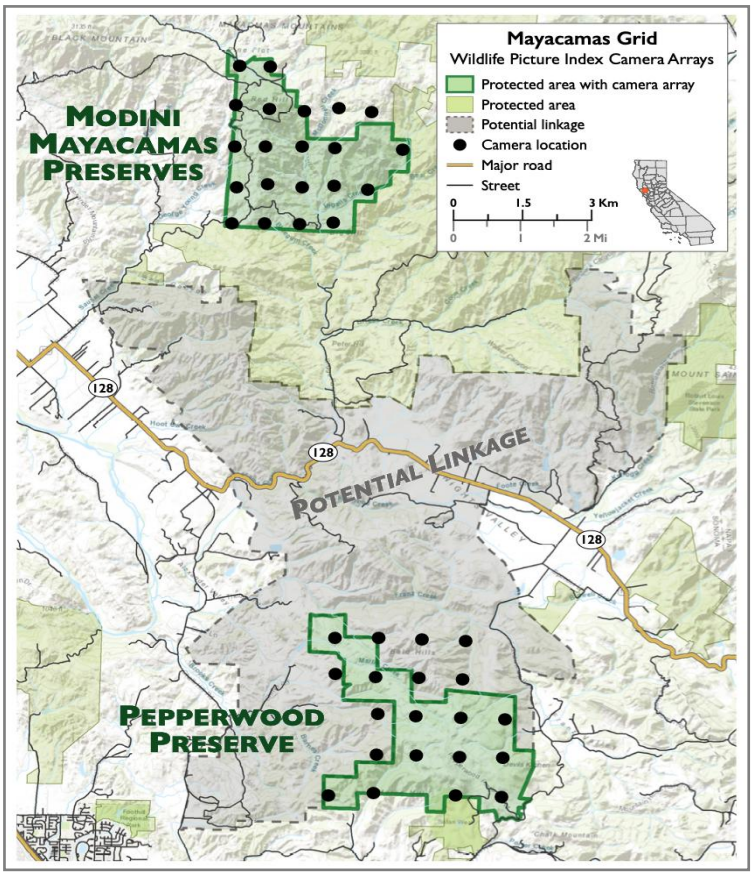

Figure 6: This map depicts the current location of the two wildlife camera grids currently maintained and operated by Pepperwood. Potential corridors linking these grids are highlight in grey.

In 2012, Pepperwood was the first site in North America to implement the standardized Wildlife Picture Index (WPI) method (static camera grid at 1-km distances) for studying wildlife populations and tracking occupancy over time at the landscape level. Data from the camera traps provide a non-invasive and non-biased measurement of biodiversity for medium and large sized mammals and allows us to calculate the Wildlife Picture Index (O'Brien et al. 2010). The WPI is a standardized unit-less metric that can be compared across space (from local sites to global biomes) and across time to detect relative changes in diversity. This camera design also allows us to calculate detection rates and occupancy statistics for individual species up through trophic and community levels. Our Sentinel Site project includes 20 camera traps at Pepperwood (installed 2012) and 20 traps at Modini Preserve (owned by Audubon Canyon Ranch, installed 2013) about nine miles to the north of Pepperwood (Figure 6).

Pepperwood's WPI project objectives are to:

1. Gather baseline occupancy estimates and understand trends in biodiversity, and individual species and trophic-level health.
2. Test hypotheses regarding how the Pepperwood and Modini Preserves function as habitat cores and corridors for wildlife (e.g. mountain lions, bears, bobcats.).
3. Assess how environmental drivers and management strategies may be affecting wildlife.

4. Evaluate how disturbance (e.g. fire, drought, human activity, forest thinning) affect wildlife occupancy.

Following successful implementation of WPI monitoring at two sites, Pepperwood has become a regional advisor in the rapidly growing field of camera trap data collection, management, and analysis (Figure 7).

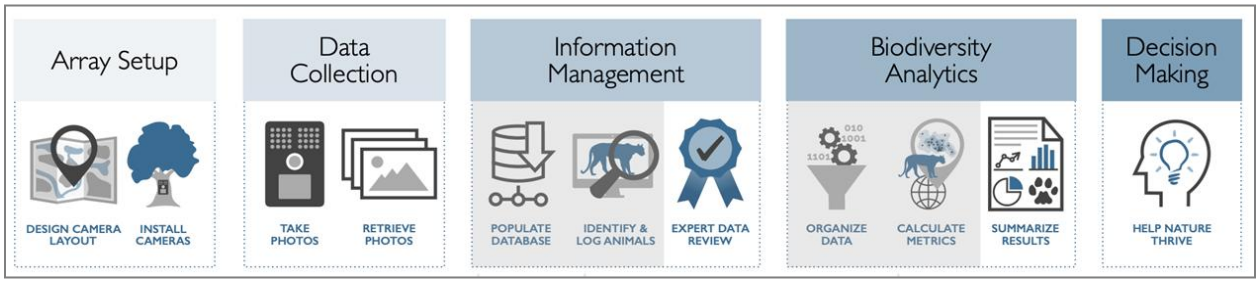

Figure 7: The workflow for Pepperwood's Wildlife Photo index (WPI) program. Boxes depicted in grey are time intensive.

Pepperwood has developed a detailed data management protocol and served as the primary organizer of the Bay Area Wildlife Observer Network. The 40 cameras that Pepperwood manages generate approximately 750,000 photographs a year that are catalogued by volunteers, interns from the Santa Rosa Junior College, and staff. Since project inception we have documented use of the preserves by locally uncommon species including American badger (*Taxidea taxus*), burrowing owl (*Athene cunicularia*), North American porcupine (*Erethizon dorsatum*), ringtail cat (*Bassariscus astutus*), and more.

Pepperwood has developed a standardized database to organize the WPI photo data collected at Pepperwood and Modini since 2012-2013 in a queryable format. We use customized scripts to automate WPI database updates and generate summary statistics for biodiversity metrics. We are currently exploring the use of machine learning algorithms to automate species identification in photos.

Proposed:

- Continue calculating detection rates and develop occupancy models for a subset of mammals.
- Continue testing of new computational and cloud-based tools with artificial intelligence that may potentially increase the efficiency of data processing and analysis. Standardized, cloud-based data management platforms can reduce data storage needs and ensure data consistency; and machine learning algorithms for data processing and analysis can save thousands of hours in data handling time.
- Evaluate how wildlife respond (1) to fire by comparing biodiversity metrics using data collected before, during, and after the 2017 Tubbs fire; (2) to the historic drought of

2013-2016; and (3) to forest thinning, prescribed fire and other planned management activities.
    - Increase research impact by partnering with other sites that have pre-/post-fire wildlife data and collaborate on publications (e.g. Dr. Justin Brashares Lab at UC Berkeley).
- Expand camera network to include camera grids in the 10+ counties in the greater San Francisco Bay Area region and provide user training, create a scientific and analytical working group, and adopt a shared data platform (utilize machine learning tools) and analytics.
- Expand wildlife camera research to include assessing connectivity of preserved lands and modeled corridors. Assess how wildlife use and movement through these areas changes over time under a warmer, drier climate and under increased landscape alteration pressures.
- Upgrade to wireless camera technology, solar power sources, and connect Pepperwood's wildlife cameras to the existing radio communication network. Wireless and/or solar-powered wildlife cameras can automate labor-intensive activities (e.g. collecting data, routine camera servicing) and prevent interruptions in data collection by providing near real-time alerts about camera malfunction allowing us to quickly service the camera and ensure uninterrupted data collection. Designed with an inbuilt transmitter or a SIM card from a cellular carrier, wireless cameras transmit images electronically and in near real-time. Transitioning from batteries to solar cells as the primary camera power source will also reduce the number of service visits to each camera (e.g. to change batteries) while alleviating camera down time due to battery failure.
- Install acoustic sensors to assess native bat species presence, abundance, and habitat preference. Consider co-locating acoustic sensors in long-term forest monitoring plots where forest thinning is proposed near to permanent water sources (CDFW grant opportunity).
- Expand collaborations with Audubon Canyon Ranch's *Living with Lions* project (tracking movement and behavior of mountain lions) to better understand habitat use and mountain lion behavior.
- Expand collaboration with newly forming Sonoma County Black Bear Collaborative with goals of better understanding habitat use, abundances and decreasing potential for human conflict.
- Conduct genetic surveys of large mammals (i.e. black bear, mountain lion) by collecting fur and/or scat.

- Expand mammal surveys to include animals that might be vulnerable to wildfire and prescribed burning in forest communities, such as documenting the density of woodrat nest sites before and after management activities.

Birds

Current:

Pepperwood started contributing to the North American Breeding Bird Survey (BBS) in 2007. The BBS is an international, long-term, avian monitoring program, led by the USGS and international partners, and serves as a primary source of population trend and distribution information for most North American birds. At Pepperwood, specialized staff and volunteers conduct annual point count surveys at 38 points across the preserve three times between April-June to measure bird abundance, diversity, and breeding behavior. Breeding bird species richness is generally stable at Pepperwood, ranging from 55-70 species (Figure 8). However, individual species' abundance trends are variable year to year and can serve as an indicator of ecosystem health, especially for climate-sensitive species.

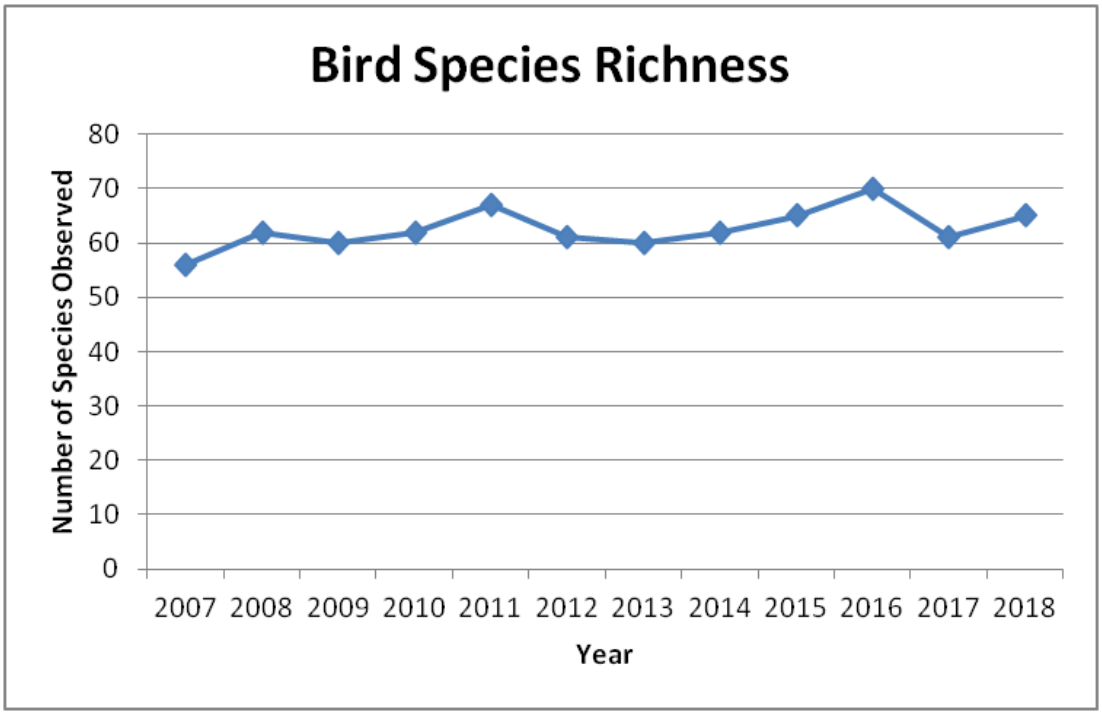

Figure 8: Bird species richness through time. This data was collected as part of Pepperwood's annual breeding bird survey, and is meant to highlight the steady values in species richness despite oscillations in individual species counts.

Pepperwood is a partner and field site for the *Soundscapes to Landscapes* project (https://soundscapes2landscapes.org/) that uses citizen scientists in the collection of field data

on bird diversity through bioacoustics. Soundscapes to Landscapes is testing the predictive strength of spaceborne hyperspectral, LiDAR, and synthetic aperture radar sensors to inform bird species distribution modeling.

Pepperwood is also a site that is monitored through the Sonoma County Bird Atlas and Christmas Bird Count for Kids.

Proposed:

- Conduct additional analyses to assess questions of habitat sustainability, bird population trends, habitat associations, and response to disturbance (e.g. drought and fire).
- Design and implement bird monitoring (e.g. point counts, acoustic sensors) before and after Douglas-fir thinning treatments (CDFW grant opportunity).
- Expand monitoring to include months when birds are overwintering and/or migrating, providing additional insight into migration routes, phenology, habitat and food preferences, species distributions, and how these patterns may be altered by climate change.
- Expand monitoring to evening hours during peak owl activity. Monitor for barred owl (*Strix varia*), which is considered an invasive species newly arrived to our region and threatens spotted owl (*Strix occidentalis*) populations. Both species have been documented at Pepperwood.
- Consult with bird experts to identify bird species captured by the Wildlife Picture Index cameras.

Reptiles and Amphibians

Pepperwood hosts a diverse suite of herpetofauna with documentation of 17 reptile and 13 amphibian species (Gillogly et al. 2017). Many of these species are considered climate-vulnerable, especially amphibians as they rely on water availability for a major portion of their life cycle. Pacific giant salamander (*Dicamptodon ensatus*) larvae can be found in perennial pools including those in Redwood, Martin and Rogers Creeks. Pepperwood is one of the few preserves in California where all three species of newts (genus *Taricha*) that are native to California can be found. We do not currently have any reptile and amphibian monitoring projects that are part of the Sentinel Site.

Proposed:

- Conduct field surveys to map habitat use, breeding behavior, and demographics in target species (e.g. Pacific giant salamander, foothill yellow-legged frog (*Rana boylii*), California newt (*Taricha torosa*), rough-skinned newt (*T. granulosa*), red-bellied newt (*T.*

rivularis), Ensatina (*Ensatina* spp.), black salamander (*Aneides flavipunctatus*), and western pond turtle).

- Develop an integrated pond monitoring program that captures real-time physical conditions and links those measurements with biological utilization of the pond. Specifically, the goal is to develop a monitoring project that tracks the utilization of ponds by amphibians and reptiles. This would be an integrative project incorporating meteorology, hydrology, water chemistry and biology. Drift fences with motion triggered cameras would capture the flux of amphibians and reptiles (e.g. western pond turtle) into and out of the ponds during breeding seasons. Additionally, strategically located cover boards near the ponds would inform resident times for species and how those resident times correspond to dynamic meteorologic, hydrologic and soil properties of these unique habitats.
- Consider adopting a herpetological cover board survey conducted by Sonoma State University at Pepperwood since 2014. Consider expanding upon the current cover board design, which centers on pond proximities, to a stratified network that examines trends in the presence or absence of species at seasonal and long-term timescales.
- Expand use of wildlife cameras to capture activity patterns and habitat use of target reptiles and amphibians (e.g. Hobbs Active Light Trigger (HALT) camera is designed to capture ectothermic animals).
- Conduct amphibian and reptile monitoring pre- and post-prescribed fire applications in forested systems to document immediate shifts in community composition and abundances following fire, while tracking their recovery long-term.
- Consider routine monitoring for amphibian pathogens, such as chytrid fungus (*Batrachochytrium salamandrivorans*), and disease-population dynamics.

Invertebrates

Pepperwood currently has no formal invertebrate research being conducted. Invertebrate specimens have been collected at the preserve, with a small collection stored on-site and additional collections housed at the California Academy of Sciences. Regular documentation of ant species are made as part of a CAS ant identification course. We do not currently have any invertebrate monitoring projects that are part of the Sentinel Site.

Proposed:

- Implement a standardized butterfly monitoring program to track changes in phenology (e.g. emergence times), species diversity, and abundance (e.g. Pollard Walk, https://www.pollardbase.org/).
- Implement species-specific monitoring of specialized butterflies that may be sensitive to climate change. For example, the CA dogface butterfly (*Zerene eurydice*) which uses the

rare Napa false indigo (*Amorpha californica* subsp. *napensis*) shrub as its host plant. Napa false indigo is associated with cooler, north-facing slopes that are considered climate-sensitive communities and may be at risk in a warmer, more arid future.
- Invite expert entomologists and arachnologists to use the preserve as a field collection and research site.
- Conduct post-fire wood borer and bark beetle infestation censuses.
- Consider implementing pollinator surveys and targeting potentially climate-sensitive species, such as native solitary bees.

Emergency Alert Systems

In the wake of the 2015-2019 fire and flood seasons, the value of Pepperwood's field station, with vantage points able to scan thousands of miles of Northern California's mountains and valleys, has emerged as a real-time source of data to inform hazard warnings and first response in concert with local water and fire agencies.

Alert Wildfire Camera

Current:
In partnership with Sonoma Water, University of Nevada Reno, University of Oregon, University of California San Diego, and Sonoma State University, Pepperwood has installed two fire cameras. These cameras are part of an expanding North Bay and state-wide network. The cameras have a 360 degree range and 32x optical zoom for pinpointing ignition sites as well as visible and near infrared bands that allow 24/7 visibility. CAL FIRE and local first responders have administrative access and camera controls that support fire assessment and response. A live feed is available from the two fire cameras located at Pepperwood West (High Hill) and Pepperwood East (Hill 1524) is available (Figure 9).

Proposed:
- Connect to CENIC microwave internet from Sonoma State University.

- Explore applications of fire camera data collaborative with ALERTWildfire Network partners.

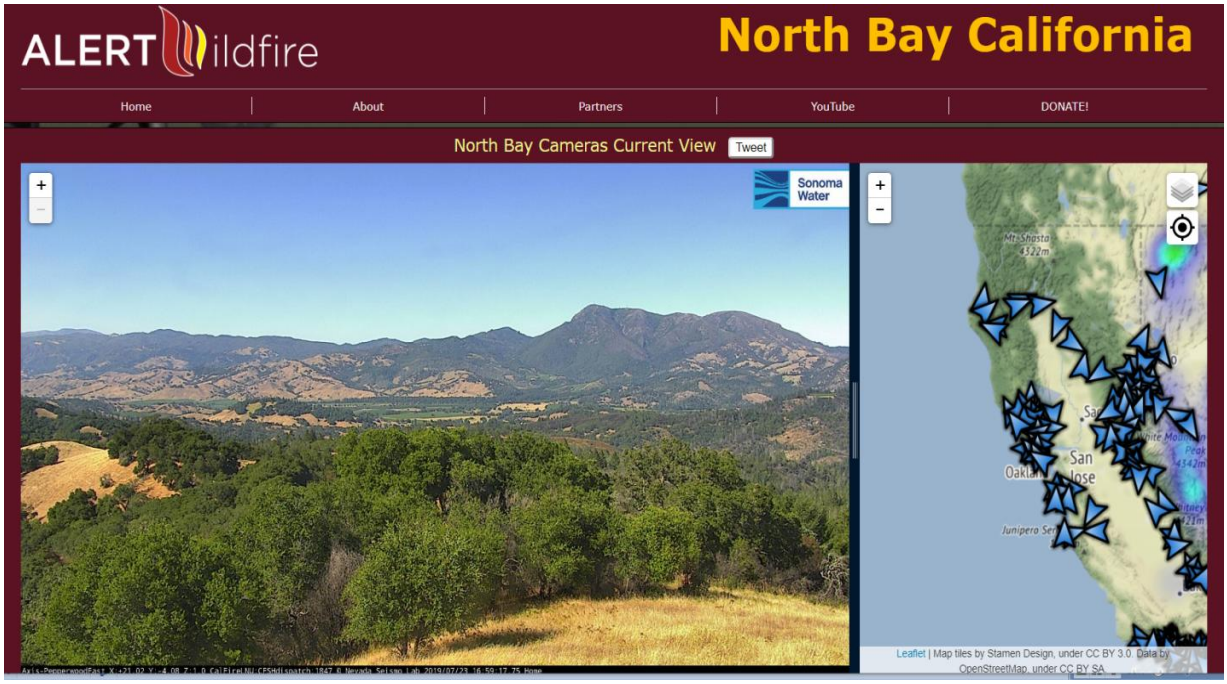

Figure 9: The publically viewable camera interface for the Pepperwood East (Hill 1524) fire Camera (http://www.alertwildfire.org/northbay/index.html

Sonoma Water Emergency Alert Rain Gauge

Current:

Pepperwood is hosting a Sonoma Water Emergency Alert rain gauge that provides early monitoring systems for flash floods and debris flows in burn area. A network of rain and stream flow gauges have been installed within and downstream of the areas burned by the October 2017 wildfires, providing real-time data to weather modelers who alert residents when flash floods or debris flows may be at higher risk. This information informs fire recovery planning, regional debris flow models, and local risk assessments.

Proposed:

- Continue to test and calibrate Sonoma Water's Emergency Alert system. Using two of our independent data sources, we have been helping them identify the need to modify communications settings. The redundancy of the measurements provides quality control in direct service to our community.

Pepperwood Radio Communication Network

Pepperwood's original radio network was designed using a mesh topology and was operational from February 2015 through October of 2017, when most of the infrastructure was destroyed in the Tubbs Fire. Pepperwood is currently rebuilding a new point to point modular radio communication network that will serve as the backhaul for the 358 (and growing) downfield data streams. Through this network Pepperwood has on-demand, real-time data access as well as automated uploading of data to a web based hosting platform.

Figure 10: The High Hill gateway for the Long Range (LoRa) radio telemetry being piloted at Pepperwood.

Current:

In anticipation of the needs of future research, Pepperwood and its radio network contractor, Day Systems, have designed this network with augmented power and bandwidth. This approach will allow for the seamless integration of other monitoring stations onto the network. Beyond data acquisition this system will allow for the real time monitoring of sensor and datalogger function and provides remote access to more rapidly troubleshoot and correct sensor and datalogger issues.

In the spring of 2019, Long Range (LoRa) radio telemetry was introduced to Pepperwood by researchers from Carnegie Mellon University (Mountain View, CA) as a pilot program to test the capabilities of the system in topographically heterogeneous landscapes. The LoRa network gateway was erected in April 2019. This project is ongoing but will allow Pepperwood to automate data retrieval from many of its hydrologic monitoring locations. Furthermore, Pepperwood will serve as a demonstration site for the use of LoRa telemetry in similar landscapes.

Proposed:

- Complete the installation of phase two of Pepperwood's radio network which will bring an additional 17 smaller meteorological and soil moisture stations onto the network.
- Complete the preliminary sensor installation for the LoRa system.

- Continue collaborating with researchers at USGS, Carnegie Mellon and elsewhere to identify and develop further monitoring objectives that can be brought onto the LoRa Network.

Cloud-based Data Management Platforms

In collaboration with partners and Visiting Scholars, Pepperwood has accumulated a valuable data record, ranging from time-series of climate and hydrology, to vegetation and wildlife data. We will continue to organize, document, and provide easy access to historic and current data. We are adopting a standardized project-based data management planning process that will identify key data dissemination repositories and platforms.

Current:
Climate and Hydrology:
In partnership with Sonoma Water, Pepperwood is connecting 378 climate and hydrology data streams to Contrail's One Rain cloud-based data hosting platform. Pepperwood's data will be shared directly with Sonoma Water and (where applicable) integrated into their flood modeling and forecasting efforts. The data can be accessed by partners and the general public through a customized dashboard. Pepperwood will set privacy for each dataset (default as publically available). The functionality and customizability of this One Rain platform is expansive and incorporates all aspects of data management, including:

- Customizable dashboards, allowing for rapid viewing and understanding of critical data streams.
- Quality controls that can be set for incoming data preventing backlog.
- Quality control can be applied retroactively if issues are discovered post upload.
- Automated data uploads can be customized to provide data at desired frequency.
- Data thresholds can be programmed so that we are notified via email in the event of a sensor malfunction.
- Interactive maps, allowing for a spatial visualization of available data across the preserve.
- On-the-fly graphing and visualization tools that allow the user to rapidly assess data values and trends in a user selected time frame.
- Data can be exported directly from the user interface allowing for rapid dissemination.
- Raw data can be manipulated, combined and binned to create new custom data streams with the platform.

The capabilities summarized above will save time and effort on the part of Pepperwood staff. Above all, this platform will ensure the collection and dissemination of accurate, high quality

data that can be leveraged to inform management and adaptation decisions in the highly dynamic coast range ecosystems of California.

Wildlife: Pepperwood has been working with Conservation International to provide input on the design and testing of the Wildlife Insights platform (https://wildlifeinsights.org/). We are evaluating a range of new computational tools to assess their potential to increase efficiency of data processing, analysis, and reporting.

Proposed:
Climate and Hydrology:

- Customize Pepperwood's Sonoma County OneRain climate and hydrology dashboard to support our reporting needs (https://sonoma.onerain.com/home)
- Train stakeholders to interpret and access data through online dashboard
- Provide Application Programming Interface (API) to data for partner organizations, as requested.

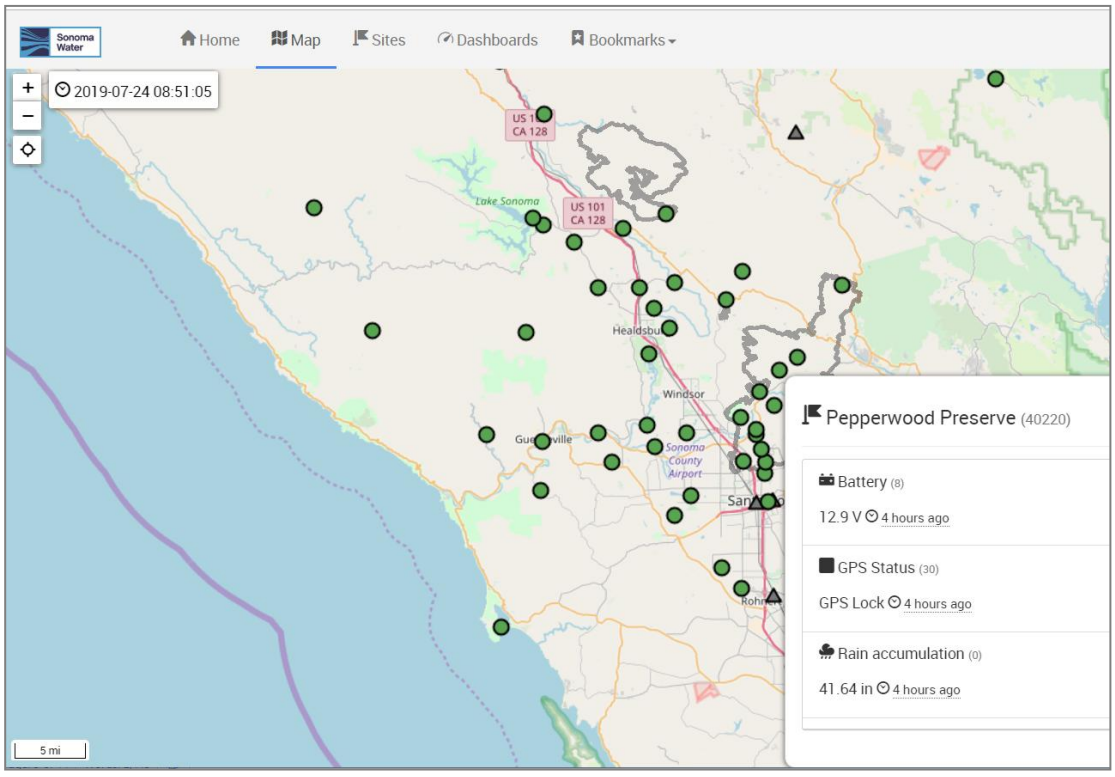

Figure 11: The county-wide extent of all monitoring locations on the Sonoma County OneRain dashboard. Pepperwood is hosted by the Sonoma county platform and represents an area of dense instrumentation in this county-wide monitoring network.

Wildlife:

- Continue to explore publicly accessible custom solutions or data repositories for housing data generated by wildlife cameras.
- Explore additional repositories for uploading observation data, such as eBird and eMammal.

Remote Sensing and Geographic Information Systems

We expect remote sensing to play an increasingly important role in long-term natural resource assessment and monitoring. In our research at Pepperwood, we utilize a range of remote sensed products. We work closely with Visiting Scholars at Sonoma State University, USGS, UC Berkeley, and other organizations to employ our field based data streams for validation.

Current:

Pepperwood utilizes remote sensing and geographic information systems (GIS) to support both long-term Sentinel Site components and shorter term research projects. In 2012 Pepperwood completed a preserve-wide vegetation map. We also regularly use Sonoma County's LiDAR data generated in partnership with NASA and HyspIRI mission24, a high resolution AVIRIS-NG (2 meter pixel) hyperspectral imaging (http://sonomavegmap.org/, Hochberg et al. 2015).

Following the October 2017 wildfires, Pepperwood has catalyzed regional modeling efforts that characterize and quantify the drivers of wildfire. Many of these spatial layers have been mapped and developed specifically for Sonoma County. Mapping products include ladder fuels, soil burn severity, canopy damage and fire perimeters. Modeling outputs directly following the fire events were risk-oriented and presented risk estimates for high runoff, flooding, debris flow and mass wasting events. Pepperwood has also worked with partners to develop a fine scale (5 m) fuel model (Tukman Geospatial). Pepperwood has played a critical role in the ground validation of these map and model outputs.

Proposed:

- Assess how new standard satellite and airborne sensors may be leveraged to evaluate other site-specific parameters in time series, such as vegetation productivity indicators, soil moisture indicators, and climate derivatives such as spatially distributed cloud cover and evapotranspiration estimates.
- Use remotely sensed vegetation metrics to extrapolate ground based point measurements. For example, addition of eddy covariance flux towers to measure evapotranspiration would provide Pepperwood with the opportunity to use NDVI to extrapolate these measurements across similar ecosystems (Goulden et al. 2012).

- Upgrade ESRI-based Geographic Information Systems software to support Pepperwood research and simplify spatial data sharing with agency partners (e.g. Sonoma County). This includes transitioning to ArcGIS Pro as well as purchasing ArcGIS Online subscriptions to facilitate faster sharing of data between Pepperwood and its partners.

Summary and Next Steps

Pepperwood's Sentinel Site activities measure how spatial and temporal variability in climate drives ecosystem processes in Mediterranean systems. Our research covers a broad range of questions about the structure, function, and conservation of our region's natural and social resources in an era of rapid climate and land use change. Understanding these relationships between physical and biological factors requires integrated, multi-disciplinary research that spans spatial scales and timeframes.

Pepperwood's Research and Preserve Management (RPM) team manages the Sentinel Site monitoring and research projects. The RPM team has developed a set of Objectives and Key Results (OKRs, 2020-2025) that chart an ambitious course for the next five years. These OKRs, in combination with this *Climate and Ecosystem Sentinel Site Plan* define our priorities and outline next steps towards increasing the impact of our program management, field station facilities, adaptive management, and Sentinel Site research and monitoring.

Pepperwood is an innovation hub and test site for new methods, models, and technologies. We will continue to test new equipment and work with partners to share and standardize protocols. Internally, the RPM team is actively developing standardized databases, creating and utilizing scripts to make repeated analyses more efficient, and testing new cloud-based tools and custom solutions for managing climate, hydrology, and wildlife data. These practices will improve data quality, help us analyze and disseminate results faster, and as a result, better inform decisions on time scales relevant to resource management and conservation. It is an ongoing challenge for us to maintain and build upon technology and analysis techniques and stay at the cutting edge of conservation science.

Pepperwood has built a strong foundation from which we can track and monitor ecosystem health over the next century. As we move forward, we strive to develop more integrated Sentinel Site project sites - places that comprehensively measure climate, hydrology, and wildlife. For example, we propose the creation of a demonstration site at Turtle Pond that will enable us to better communicate with stakeholders, students, and the general public about the impacts of climate change. At larger scales, we are working with partners to collaboratively design a systematic, state-wide wildlife camera monitoring plan. Closing several significant gaps

in our understanding of the distribution, life-history, and conservation status of reptiles, amphibians, invertebrates, and microbiotic communities is a critical next step.

Pepperwood is uniquely positioned to advance regional understanding of the hydrologic cycle in California Coast ranges. Working closely with the Terrestrial Biodiversity and Climate Change Collaborative (TBC3), Pepperwood has collected nearly a decade of baseline climate and hydrology information that is used to calibrate the Basin Characterization Model. In this plan we outline approaches to closing critical gaps in our understanding of the water balance and predicted future conditions.

Following significant equipment losses that Pepperwood experienced in the Tubbs Fire (October 2017), the primary focus of Sentinel Site staff over the past two years has been rebuilding the sensor and radio communication network while rapidly documenting in-field ecosystem response to the fire. We have completed the first phase of rebuilding our communication network (radio network backbone, four replacement weather stations, fire cameras, emergency flood gauge). In 2019-2020, we will complete the installation and networking of 17 simplified weather stations that complement long term forest research. A customized web platform we are developing will make our data directly accessible to Sonoma Water and widely accessible to stakeholders and the general public.

Pepperwood is actively expanding our climate and fire hazard research and partnerships. We aim to fill critical knowledge gaps with respect to our region's wildfire preparedness, first response capacity, recovery strategies, and long-term resilience. Building upon ten years of accumulated data and analysis, the Sentinel Site provides a unique foundation for designing and deploying a state-of-the-art early warning and situational awareness system for fire hazards throughout California and beyond. In the next five years we aim to serve as the backbone organization for a collaborative network of computer science, remote sensing, and artificial intelligence partners to incorporate multiple data streams into integrated decision support platforms to help resource managers, policy makers, landowners, and everyday citizens more quickly adapt to living in a fire prone region.

As a founding member and co-chair of the Terrestrial Biodiversity and Climate Change Collaborative (TBC3), Pepperwood will continue to utilize TBC3 as a science advisory network and leverage annual meetings to identify knowledge gaps, develop integrated research initiatives and test conservation planning tools and methods. TBC3 advisors will play a critical role in helping prioritize, developing proposals, and phasing the proposed additions and refinement of the Pepperwood Sentinel Site outlined in this plan. In the next five years, Pepperwood will continue to build relationships with researchers and practitioners to augment

our Sentinel Site hydrology, nutrient cycles, and atmospheric science. Additionally, we will continue to deepen partnerships with the University of California Natural Reserve System and the California Department of Fish and Wildlife to pilot the Sentinel Site research and monitoring approach across the state of California. And, lastly Pepperwood's participation in international networks including the Chile-California Conservation Network, Organization of Biological Field Stations, International Lands Network and International Society of Mediterranean Ecology (MEDECOS conference) will further expand our growing role as a world class field station.

Acknowledgements

We gratefully acknowledge the many colleagues who contributed their intellectual input and reviewed earlier versions of this plan or related proposals. We provide special thanks to the members of the Terrestrial Biodiversity Climate Change Collaborative (see TBC3.org) including co-chair Dean David Ackerly of UC Berkeley's College of Natural Resources; Alicia Torregrosa, Alan Flint, Lorraine Flint of the US Geologic Survey; and, Dr. Stuart Weiss of Creekside Center for Earth Observation. We are also grateful for the collaboration of many local land and water agencies, including Sonoma Water and the Mayacamas to Berryessa Landscape Connectivity Network (M2B) for advising on data needs for applied land, water and wildlife management. We also thank our sister field stations of the Organization for Biological Field Stations, especially those that hosted site visits as part of our NSF Strategic Planning Grant activities, and the University of California's Natural Reserve System, under the leadership of Dr. Peggy Fiedler. We also thank colleagues at California natural resources agencies including Dr. Christina Sloop of the Department of Fish and Wildlife, Mike Anderson of the Department of Water Resources, and all our colleagues at CAL FIRE. And thanks to the many organizations who provided their strategic plans as models including California Academy of Sciences, Audubon Canyon Ranch, Sonoma Land Trust, Sonoma State University's Center for Environmental Inquiry, the Center for Western Water and Weather Extremes at Scripps, UC San Diego, and Point Blue Conservation Science. We thank all the student interns, many from the Santa Rosa Junior College, our TeenNat Alumni, and the Pepperwood volunteer stewards, members, donors and citizen scientists who make our Sentinel Site possible. And lastly, words cannot express our appreciation for the dedicated and talented Pepperwood staff and board, including the foundational leadership of Herb and Jane Dwight (Co-Founders), Michael Gillogly (Preserve Manager), and Steve Barnhart (Academic Director Emeritus).

References

Ackerly, D., Oldfather, M., Britton, M., Halbur, M., and Micheli, L. 2013. Establishment of woodland vegetation research plots at Pepperwood Preserve. Page Terrestrial Biodiversity Climate Change Collaborative. Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA.

Ackerly, D. D., Ryals, R.A., Cornwell, W.K., Loarie, S.R., Veloz, S., Higgason, K.D., Silver, W.L., and Dawson, T.E. 2012. Potential impacts of climate change on biodiversity and ecosystem services in the San Francisco Bay Area. California Energy Commission.

Ackerly, D.D., Cornwell, W.K., Weiss, S.B., Flint, L.E., Flint, A.L. 2015. A Geographic Mosaic of Climate Change Impacts on Terrestrial Vegetation: Which Areas Are Most at Risk? PLoS ONE 10(6).

Ackerly, D.D., Kling, M., Clark, M., Papper, P., Oldfather, M., Flint, A., and Flint, L., (in press) Topoclimates, Refugia, and Biotic Responses to Climate Change. Frontiers in Ecology and Evolution.

Ackerly, D., A. Jones, M. Stacey, B. Riordan. (University of California, Berkeley). 2018. San Francisco Bay Area Summary Report. California's Fourth Climate Change Assessment. Publication number: CCCA4-SUM-2018-005.

Chornesky, E. A., Ackerly, D.D., Beier, P., Davis, F.W., Flint, L.E., Lawler, J.J., Moyle, P.B., Moritz, M.A., Scoonover, M., Byrd, K., Alvarez, P., Heller, N.E., Micheli, E.R., Weiss, S.B. 2015. Adapting California's ecosystems to a changing climate. BioScience 65:247–262.

DeNevers, G. 2013. Pepperwood Preserve Vascular Flora, 3rd edition. Page (P. Rockwood, M. M. Halbur, and M. Gillogly, Eds.). 3rd edition. Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA.

Fenn, M. E., Allen, E.B., Weiss, S.B., Jovan, S., Geiser, L.H., Tonnesen, G.S., Johnson, R.F., Rao, L.E., Gimeno, B.S., Yuan, F., Meixner, T., and Bytnerowicz, A. 2010. Nitrogen critical loads and management alternatives for N-impacted ecosystems in California. *Journal of Environmental Management*, *91*(12), 2404-2423.

Flint, L. E. and Flint, A.L., 2012. Downscaling future climate scenarios to fine scales for

hydrologic and ecological modeling and analysis. Ecological Processes, 1(1), 2.

Gillogly, M., Dodge, C., Halbur, M., Micheli, L., McKay, C., Heller, N., and Benson, B. 2017. Adaptive Management Plan for Pepperwood Preserve, Sonoma County, CA. A Dwight Center for Conservation Science Technical Report product of Terrestrial Biodiversity Climate Change Collaborative, p. 286.

Goulden, M. L., Anderson,R. G., Bales, R. C., Kelly, A. E., Meadows, M. , and Winston, G. C. 2012. Evapotranspiration along an elevation gradient in California's Sierra Nevada,J. Geophys. Res.,117.

Heller, N. E., Kreitler, J., Ackerly, D.D., Weiss, S.B., Recinos, A., Branciforte, R., Flint, L.E., Flint, A.L., and Micheli, E. 2015. Targeting climate diversity in conservation planning to build resilience to climate change. Ecosphere 6(4):65.

Halbur, M., Kennedy, M., Ackerly, D., Micheli, L., and Thorne, J. 2013. Creating a detailed vegetation mapfor Pepperwood Preserve. Terrestrial Biodiversity Climate Change Collaborative. Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA.

Hesed, K.M. 2012. Uncovering salamander ecology: a review of coverboard design. Journal of Herpetology 46.4 : 442-450.

Hobbs, M.T., Brehme, C.S. 2017. An improved camera trap for amphibians, reptiles, small mammals, and large invertebrates. PLoS ONE 12(10): e0185026.

Hochberg, E. J., Roberts, D.A., Dennison, P.E. & Hulley, G.C. 2015. Special issue on the Hyperspectral Infrared Imager (HyspIRI): Emerging science in terrestrial and aquatic ecology, radiation balance and hazards. Remote Sens. Environ. 167, 1–5.

McIntyre, P. J., 2015. Twentieth-century shifts in forest structure in California: denser forests, smaller trees, and increased dominance of oaks. Proceedings of the National Academy of Sciences 112.5: 1458-1463.

McLaughlin, B.C., Ackerly, D.D., Klos, P.Z., Natali J., Dawson, T.E., Thompson, S.E. 2017. Hydrologic refugia, plants, and climate change. Global Change Biology (8):2941-61.

McLaughlin, J. 2005. Geology of Pepperwood. Santa Rosa, CA.

Micheli, L. and DiPietro, D. 2013. North Bay Vital Signs: An Integrated Ecosystem-Climate Monitoring Framework for Sonoma County. Report of the North Bay Climate Adaptation Initiative Science Working Group.

Micheli, L., Flint, L., Flint, A., Weiss, S., and Kennedy, M. 2012. Downscaling Future Climate Projections to the Watershed Scale: A North San Francisco Bay Case Study. UC Davis San Francisco Estuary and Watershed Science, 31 pp.

Micheli, E., Flint, L., Veloz, S., Johnson (Higgason), S., and Heller, N. 2016. Climate Ready North Bay Vulnerability Assessment Data Products: 1. North Bay Region Summary. A technical memorandum prepared by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA, for the California Coastal Conservancy and Regional Climate Protection Authority, 38 pp.

Micheli, E., Dodge, C., Flint, L., and Comendant, T. 2018. Climate and Natural Resource Analyses and Planning for the North Coast Resource Partnership: a technical memorandum summarizing data products. A final report prepared by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA, for West Coast Watershed and the North Coast Resource Partnership.

O'Brien, T.G, Baillie J.E.M, Kruger, L., and Cuke, M. 2010. The Wildlife Picture Index: monitoring top trophic levels. Animal Conservation, 13:4: 335-343.

Oldfather, M. F., Britton, M. N., Papper, P. D., Koontz, M. J., Halbur, M. M., Dodge, C., and Ackerly, D. D. 2016. Effects of topoclimatic complexity on the composition of woody plant communities. AoB Plants. 8, plw049. doi:10.1093/aobpla/plw049.

Porzig, E., Seavy, N.E., DiGaudio,R. T., Henneman, C. and Gardali, T. 2018. The Rangeland Monitoring Network Handbook V2.0. Point Blue Conservation Science, Petaluma, California.

Scholl, M. A., Torregrosa , A., and Coplen, T. B. 2014. Determining the hydrological importance of coastal fog in Northern California using stable isotopes of water. Poster presentation at American Geophysical Union, San Francisco, CA.

Torregrosa, A. 2013. Ecologically-relevant fog data sets to improve San Francisco Bay Area climate and hydrology projections. A final report prepared by the Dwight Center For Conservation Science at Pepperwood, Santa Rosa, CA for the Gordon and Betty Moore

Foundation, 99 pp.

Tonnesen, G; Wang, Z; Omary, M; Chien, CJ. 2007. Assessment of Nitrogen Deposition Modeling and Assessment. California Energy Commission PIER Energy-Related Environmental Research, CEC-500-2005-032.

Vanderbilt, K. and Gaiser, E. 2017. The International Long Term Ecological Research Network: a platform for collaboration. Ecosphere, 8(2).

Appendices

Appendix A: Pepperwood Science Questions

Science to support management of Mediterranean ecosystems

Introduction

The goal of Pepperwood's science program is to advance understanding of how spatial and temporal variability in climate drives Mediterranean watershed and ecosystem processes. Understanding the relationship between physical and biological factors in our environment requires cross-disciplinary and multi-disciplinary research. Our science questions span multiple disciplines, spatial scales, and timeframes and address a broad range of questions about the structure, function, and conservation of our region's natural and cultural resources in an era of rapid change. In developing these questions, we asked "what would land and water managers of the year 2100 wish we had measured?"

Pepperwood is uniquely positioned to advance the knowledge base of the California Coast ranges with our Sentinel Site Research and Visiting Scholar Program. Our Sentinel Site is dedicated to tracking inland watershed health over time by collecting a long-term record of physical and biological condition. We measure indicators of ecosystem health (e.g. temperature, precipitation, species abundance, soil moisture, canopy damage, etc.) over time and space. The Sentinel Site provides nearly continuous data at multiple locations spanning Pepperwood's 3,200-acre Coast Range field station. Following the 2017 Tubbs Fire, Pepperwood is now equipped with video cameras as part of a state-wide ALERTWildfire system and a new Sonoma Water Emergency Alert Rain Gauge. Pepperwood's Sentinel Site is being leveraged by local and state first responders for real-time fire and flood hazard assessments.

The Pepperwood Sentinel Site is comprised of partnerships between many organizations, agencies, researchers, and communities working together to better understand, mitigate, and adapt to climate change. Working closely with the Terrestrial Biodiversity and Climate Change Collaborative (TBC3), Pepperwood facilitates communication between scientists and resource managers, and educates the public about issues that impact our community. At Pepperwood, we are conducting research and testing stewardship practices designed to build resilience and hasten adaptation to a rapidly changing climate.

The overarching science question that unites Pepperwood's research is:

How do environmental variability and biological diversity at a landscape scale influence the resilience of Mediterranean-type ecosystems to a changing climate?

This key question is an "umbrella" under which more detailed questions, are nested and organized by discipline and resources

Climate and Hydrology

How do temperature, precipitation, and resulting watershed hydrologic response vary over a range of spatial and temporal scales in the California Coast Ranges? What are the drivers of this variability?

- What is the impact of topography, geology, solar radiation and vegetation on the variability of local climate and hydrology?
- How do we characterize and model (e.g., USGS Basin Characterization Model) the diversity and distribution of climatic and hydrologic variables, including the partitioning of the water balance/cycle in watersheds (e.g., evapotranspiration, runoff, recharge, soil moisture storage)?
- Will physical heterogeneity decrease or increase under warming? Does that depend on whether precipitation goes up or down?
- How does the marine layer/climate impact landscape variability?
- What is the relative importance of aspect, cold air pooling, wind exposure, and other topographic factors on spatial variability in topoclimates, and how do these influences change across years, seasons and time of day?
- What is the variability of vertical variation in near-ground and lower atmosphere conditions? How does subsidence and the marine layer impact terrestrial climates? What is the influence of cold air pooling on air temperature structure? How does vegetation structure interact with near-ground air temperature structure?
- What is the relationship between frequency and periodicity of different synoptic meteorology and topoclimate variability (cold air pools, topographic heterogeneity, atmospheric rivers, etc.)?
- What are the controls on soil moisture dynamics-including soil structure, underlying geology, rates of evapo-transpiration and other aspects of vegetation demand?
- What are the controls on water supply generated by headwater watersheds to reaches downstream?
- What are the mechanics of water storage in poorly characterized components of the watershed including fractured bedrock and weathered colluvium?

- What are the controls on surface and subsurface water fluxes in ephemeral montane channels (including onset and duration of flow)?
- What are the sources of waters that comprise local surface and subsurface supplies (precipitation, groundwater, fog)? What are the residence times of these different water sources in local watersheds?
- What are the impacts of drought, flood, fire and transitions in vegetation on the hydrologic response of watersheds?
- What are the controls on fog production, structure, and spatial distribution?
- What are the controls on water content of fog events and what are the mechanisms of delivery to terrestrial and aquatic ecosystems?
- What is the contribution of fog water to terrestrial, riparian and aquatic water balances?

- Can biotic indicators, such as lichens (e.g. Niebla spp.), be used to monitor changes in fog occurrences in space and time?
- How do soil properties influence the timing and distribution of hydrologic processes across the landscape (e.g., recharge, runoff, flow onset, baseflow, drydown)?
- How do soil properties vary across the landscape?
- What is the role of deep soil moisture in controlling the timing and duration of stream flow (e.g., using neutron probes to measure deep soil moisture)?

*What are the projected impacts of **anthropogenic climate change** on the natural resources of the California Coast Range as a function of topography, geology, soils, and vegetation community?*

- How will projected climate change impact the water cycle and watershed response? (groundwater, streamflow, stream temps, soil moisture, evapo-transpiration, etc.)
- How will projected climate changes impact coastal meteorology and fog distributions?
- Will landscape heterogeneity, and associated diversity, increase, decrease or remain similar under warmer and/or drier climates?
- How will projected climate change impact vegetation species distributions, invasions and invasiveness, and successional trajectories?
- How will projected climate change impact wildlife species distributions and abundances?

Vegetation Ecology

What are the physical and biological factors that influence the distribution of vegetation communities in the California Coast Ranges?

- What are the physical and biological controls on grassland, chaparral and forest plant species distributions?
- How does variability in climate and soil hydrology impact plant distributions, growth rates, reproductive success, and range expansions or contractions?
- How does dispersal biology and soil seed banks impact species temporal and spatial distributions, including range transitions and expansions?
- What remote sensing products are ideal for conducting vegetation species mapping, seasonal monitoring, capturing phenology, etc.?
- How does vegetation species composition, including invasive species, impact hydrology, soils and biodiversity?
- How do transitions in vegetation influence hydrology (e.g. transition from grassland to shrubland, oak woodland to Douglas-fir forest, etc.)?
- Does consideration of range-wide climatic characteristics of species increase our understanding of community structure across local topo-climatic gradients?
- How can projections of climate change be used to project species or community declines or expansions?
- Are plant communities in climatic refugia (i.e. cool and/or moist landscape positions, more stable landscape positions) more or less resilient in the face of climate change?
- Are plant communities on distinct geologies (distinctive geology that buffers hydrology or plant response) more or less resilient to climate change?
- Does heterogeneity and diversity buffer vegetation response to climate change by providing more diverse seed sources in proximity?
- How does historical heterogeneity and diversity lying dormant in the soil seed bank influence vegetation community response to climate change?
- Do cooler vs. hotter locations on the landscape differ in seed rain of species that may be adapted to future conditions (e.g., test prediction that cooler spots should receive higher seed rain of warm-adapted species)?
- Where are foci for expansion of hot-adapted species? Is serpentine a nucleus for shrubland expansion?
- What are the dispersal modes of hot- and cool-adapted species? What is the role of animals for species dispersal?

What are the biological interactions between different vegetation communities and how does that influence community distributions?

- What conditions favor or inhibit the invasion of Douglas-fir into grassland, oak and chaparral communities?
- What conditions favor or inhibit the invasion of other species into distinct geologies such as serpentine?
- What conditions favor or inhibit the expansion of coyote bush into grasslands?
- What conditions favor or inhibit the invasion of non-native species?
- What conditions favor or inhibit the arrival or spread of pathogens or pests, such as sudden oak death, fungal root rot, oak moth, bark beetle, etc.?

How do temperature, precipitation, soil moisture and other climate-hydrology drivers influence plant phenology?

- How does the phenology of different plant species respond to landscape position and wet vs. dry and cool vs. warm years and seasons?
- How does the relative phenology of plants impact pollinators, consumers, plant reproductive success, etc., and vice versa?
- Does topographic heterogeneity enhance flowering duration and diversity and do these patterns impact resource availability for pollinating insects?
- Do patterns of topographic heterogeneity impact fruiting success, dispersal, and seedbank maintenance?
- How do climate-driven disturbances impact plant phenology and associated food webs (e.g. more frequent and extreme fires and the immediate loss of animal food and nectar/pollen sources followed by delayed impacts on plant reproduction in the years following fire)?

What strategies do plants use to survive drought in a Mediterranean landscape?

What are the drivers of drought stress on plants (lithologic, topographic, ecologic)?

- What are the interactions between water availability and plant traits/physiology in drought-dominated conditions (relationships between relative stomatal regulation, soil water availability, rate of soil water supply, rate of evaporative demand)?
- What are the hydraulic strategies plants use to survive drought?
- What are the key plant traits that define drought resilience and regulation of environmental water status?

- Can we predict plant populations on the landscape that are sensitive to drought and identify mortality thresholds?
- What are the characteristics of landscape positions that may serve as refugia in the face of a changing climate?
- Are the cooler spots also more stable year to year and in response to climate change?
- What factors enhance resilience of vegetation to changing climate, and where are those found on the landscape?
- Do species exhibit differential sensitivity to inter-annual climatic variation, and are differences predictable based on underlying physiology and where populations fall in the species' geographic range?
- Is spatial variability in growth predictive of species sensitivity to climate?

Wildlife and Corridor Ecology

What are the drivers of wildlife occupancy and behavior in the California Coast Ranges?

- How does the wildlife occupancy of the preserve vary over time and space?
- What is the relationship of wildlife occupancy at the Pepperwood Preserve to that of other protected areas in our region?
- How are animals moving or restricted from moving between suitable habitats?
- What is the relationship of wildlife occupancy to carrying capacity?
- What is the influence of top predator density on herbivores and trophic cascades?
- What is the impact of herbivory on plant communities? (i.e. test impacts using herbivore exclosures)?
- What is the status of wildlife demography, density, age structure, and reproductive success and how do these factors change over time?
- What are the relationships between species, guild, and multi-species occupancy on the preserve and in the region?
- How do wildlife species respond to drivers including climate, hydrology, drought, fire and land and water management?
- How does wildlife respond to changing vegetation, soil health, prescribed burning, succession and vegetation type change?
- How are species of interest using various habitat types and landscape features?
- How does proximity to roads impact wildlife?
- How does the Wildlife Photo Index method compare with other methods?
- Where are human/wildlife interactions most likely to occur on the landscape?

How do local animal populations vary through space and time? What are the drivers on species composition, distribution, and behavior?

- What is the composition of the local amphibian and reptile population and how does that vary across time and space and what are the drivers on species composition and distribution?
- What is the composition of the local bird population and how does that vary across time and space and what are the drivers on species composition and distribution?
- What is the composition of the local mammal population and how does that vary across time and space and what are the drivers on species composition and distribution?
- What is the composition of the local invertebrate population (e.g. butterflies and ants) and how does that vary across time and space
- What are the drivers of species composition and distribution?
- What are the pathogen threats to wildlife in our region and how do they impact wildlife?
- How do non-native wildlife species impact ecosystems and what are the impacts of control strategies?
- What terrestrial species currently occur within corridors surrounding Pepperwood?
- What pathways are focal animals using within corridors?
- Which creeks are providing open passage for animal movement?
- How are animals utilizing the power line corridor running between Pepperwood and Modini?
- Is there a difference in species composition and occupancy between Pepperwood and Modini Preserves?
- Are there key areas that provide critical food, water, or cover for target species in the corridor?
- How are plant communities predicted to transition in and out of the corridor?
- What are the main threats associated with invasive species in nearby corridors?
- Are there opportunities for vegetation management, restoration, or enhancement?

Restoration Ecology and Stewardship

What is the role of natural or human disturbance in vegetation ecology?

- How does grazing (deer, livestock) impact vegetation including oak seedling recruitment and invasive species dynamics and dispersal?
- How does grassland management and grazing regimes impact hydrology, soil health, and below-ground carbon storage?
- What are the relationships between fire (wildland or prescribed) and vegetation composition and dynamics?

- How does prescribed fire and fuels management impact future fire risk?
- How can post-fire regeneration methods influence native plant community composition?
- How does flood disturbance and related erosion drive patterns of riparian and wetland vegetation communities?
- How do roads and trails influence species invasions and dispersal patterns?

What is the impact of Douglas-fir removal on Oak Woodland and Mixed Hardwood Forest vegetation and ecosystem function?

- Does Douglas-fir removal enhance or support oak seedling or sapling recruitment?
- Does Douglas-fir removal enhance or support understory diversity?
- Does Douglas-fir removal alter diversity and behavior of animals in woodlands?
- Does Douglas-fir removal alter soil moisture availability?
- Does Douglas-fir removal reduce fuel loads and long-term fire risk?

What is the impact of prescribed burning on grassland and woodland communities?

- Does prescribed burning enhance grassland diversity?
- Can burning effectively reduce unwanted invasives (e.g., medusahead)?
- What is the impact of prescribed burning and fuels reduction in wooded communities on wildlife including herpetofauna, woodrats, and avifauna?

What are the most effective treatments for invasive plants and animals in Coast Range environments?

- What are the most effective treatments for noxious weed species in Coast Range environments?
- What are the most effective treatments for bullfrogs, wild turkeys and wild pigs in Coast Range environments?
- What are the long-term effects of herbicide use to control noxious weed species?

Atmospheric Pollution

- What is the degree and impact of atmospheric nitrogen deposition on the ecosystems of the California Coast Ranges?
- What are the levels of nitrate in groundwater, springs and seeps at the preserve? How does nitrate impact species composition and community dynamics?
- What are the interactions of climate change and pollutants?
- How do interactions of climate change and pollutants impact species composition and community dynamics?

- What are the interactions of grazing and nitrogen deposition in grassland, forest, and wetland communities?
- What is the relationship between biological indicators, including lichens, and rates and quantities of atmospheric pollutant deposition?
- What is the mechanism of deposition of atmospheric mercury to local ecosystems and how does that cycle through watersheds and food chains?

Remote Sensing and Biogeography

- What remote sensing tools are available to characterize landscape characteristics described above and how well do remote observations compare or correlate with ground-based data?
- How do California Coast Range ecological processes and services vary across the landscape (fragmentation, fire frequency, land use, community structure, etc.)?
- How well can terrestrial and above-canopy remote sensing technology estimate surface and canopy fire fuels relative to traditional field-based methods?
- Can remote sensing technology be used to efficiently and rapidly quantify changes in surface and canopy fuels after treatments or natural disturbances?

Fire Science

- How accurately do remote sensing products of fire severity (e.g. canopy kill, soil burn severity) compare to ground-based fire effects data?
- What is the variation among fire effects metrics (e.g. percent leaf scorch, trunk scorch heights, delayed tree mortality, etc.) in relation to modeled and observed fire severity?
- How does Douglas-fir management influence fire behavior and intensity?
- How does fire behavior and intensity affect forest, grassland and chaparral survival, regeneration, and community composition?
- How does grazing in grasslands and oak woodland (with a dominant herbaceous understory) impact fine fuels production, fire behavior and intensity, and species responses to fire?
- How rapidly does soil recover following fire (via soil infiltration)?
- How do live fuel moisture levels correlate with fire risk modeling and climatic water deficit? How does this vary among species (e.g. evergreen versus deciduous trees, shrubs) and topoclimate position?
- How does prescribed burning in grasslands and forests modify wildfire risk, behavior, and intensity?

Education and Stakeholder Engagement

- What are the impacts of education and community engagement on attitudes towards land management, protecting biodiversity and conservation science?
- What are the contributions of citizen science to research and management?
- What are Native American restoration practices inherent in traditional ecological knowledge that may be incorporated into land management practices at the preserve and in our region?
- What are the outcomes of science products generated by the Dwight Center for Conservation Science and Pepperwood's programming? How are users utilizing information? What are the impacts on our greater community?
- What are the lessons learned in the development of Pepperwood as a regional hub for science and environmental education?
- What is the importance of networks and our supportive role in the community in creating a critical mass for developing sustainable programs, addressing climate change adaptation ethics, and conducting collaborative research?
- How can Sentinel Sites serve to answer pressing local government planning and operations?
- What are the best approaches to building local acceptance and a supportive culture for large mammals (e.g., bears, mountain lions)?
- How can Sentinel Sites best engage youth?
- What are the attitudes of private land owners and residents towards local wildlife?
- What is the frequency and type of wildlife-livestock conflict?
- Are there planning processes, policies, or funding mechanisms in place that can be enhanced to provide better connectivity at Pepperwood and for surrounding corridors?

Appendix B: Pepperwood Data Management Process

The purpose of this appendix is to define policies and procedures for curating, securing, and when appropriate, sharing and/or disseminating high quality and useful data. By implementing the approach and standards outlined here, we are protecting Pepperwood data and information assets and demonstrating regional leadership.

This Data Management Plan serves as Pepperwood's guide to ensure we use efficient methods and tools for data documentation, security, data quality assurance (QA), quality control (QC). This plan primarily addresses the data and information associated with Pepperwood's Research and Preserve Management (RPM) datasets and projects, however it will be applied to Communication (COMM), Education (EDU), and Development (DEV) wherever possible. This plan will inform resource needs for data management in the context of our 2020–2025 strategic plan, particularly identifying areas where additional human resources or information technology infrastructure may be required to strengthen our data management capacity as our organization grows.

Pepperwood is committed to using best practices associated with data management. We have adopted a standardized, project-based data management planning process that considers aspects of data collection, documentation, compliance, storage, preservation, and data sharing. All new Sentinel Site and Visiting Scholar projects will be required to develop a data management plan (Using Pepperwood's DMP template), unless otherwise agreed.

Pepperwood adheres to common data management standards (e.g., Ecological Markup Language, FGDC, etc.) and disseminate datasets in widely used repositories (e.g., California Climate Commons, Data Basin, National Phenology Network, e-Bird, e-mammal, iNaturalist, USGS ScienceBase, DataOne, etc.). In general, Pepperwood supports open access to well documented datasets. We request attribution for Pepperwood datasets. We will evaluate data sensitivity and data sharing on a project by project basis and develop data agreements, as needed.

Data Management Plan Template

Project Details

1. Project title (required):
2. Lead organization (required):

3. Funder (if applicable):
4. Grant number (if applicable):
5. Project abstract (required): *Briefly summarize research project to help others understand the purposes for which the data are being collected or create*d.
6. Principal Investigator name (required):
7. Principal Investigator email (required):
8. Principal Investigator phone (required):
9. Principal Investigator ORCID ID (optional):
10. Data contact name (if different from Principal Investigator):
11. Data contact email (if different from Principal Investigator):
12. Data contact phone (if different from Principal Investigator)
13. Partner organizations (required):
14. Project approval date (required):
15. Data Management Plan status (required):
16. Date Data Management Plan Created (required):
17. Revision dates (optional):

Data Collection

18. Give a brief description of the data you will collect or create. Include the type, format, and volume of data. Include a list of data fields and definition of attributes (required). *Note: Consider the implications of data format and data volumes in terms of storage, backup and access.*
19. List any existing data or third-party sources that will be used, in each case noting its content, type, coverage, and any use constraints (required).
20. Describe how your chosen data format and/or software enable sharing and long-term access to the data (required).
21. Outline how the data will be collected and created. State which community data standards and/or methodologies (if any) will be used (required).
22. Explain how the data will be organized during the project by providing the folder structure, naming conventions, and how you will address version control (optional).
23. Explain how the consistency and quality of data collection will be controlled and documented (required). *Note: Data quality assurance may include processes such as calibration, repeat samples or measurements, standardized data capture or recording, data entry validation, peer review of data or representation with controlled vocabularies.*

Documentation and Metadata

24. Describe the types of documentation that will accompany the data to help secondary users to understand and reuse it (required). *Note: This should at least include basic details that will help people to find the data, including who created or contributed to the data, its title, date of creation and under what conditions it can be accessed.*
25. List the metadata fields that will be provided to help others identify and discover the data (required). *Note: Consider what other documentation is needed to enable reuse. This may include information on the methodology used to collect the data, analytical and procedural information, definitions of variables, units of measurement, any assumptions made, the format and file type of the data, and software used to collect and/or process the data.*
26. State the metadata standards you will use (required). *Note: Researchers are strongly encouraged to use community metadata standards where these are in place. The Research Data Alliance offers a Directory of Metadata Standards. Data repositories may also provide guidance about appropriate metadata standards.*
27. Outline how the documentation and metadata will be captured and/or created. Describe how you will capture this information and where it will be recorded, e.g., in a database with links to each item, in a "readme" text file, in file headers, etc. (required).

Ethics and Legal Compliance

28. Describe any ethical issues related to the project and how they will be managed. (required). *Note: Managing ethical concerns may include: anonymization of data; referral to departmental or institutional ethics committees; and formal consent agreements. If you are carrying out research involving human participants, you must also ensure that consent is requested to allow data to be shared and reused. Have you gained consent for data preservation and sharing? How will you protect the identity of participants if required (e.g. via anonymization)?*
29. How will you manage copyright and Intellectual Property Rights (IP/IPR) issues? State who will own the copyright and IPR of any data that you will collect or create, along with the licence(s) for its use and reuse. For multi-partner projects, IPR ownership should be covered in the consortium agreement (required).
30. Outline any restrictions needed on data sharing. Consider any relevant funder, institutional, departmental or group policies on copyright or IPR (required).

31. Explain how the data will be licensed for reuse. Consider permissions to reuse third-party data and any restrictions needed on data sharing (required).

Storage and Backup

32. Outline how the data will be stored and backed up during the course of research activities (required). *Note: Be sure to include the following details: a) state how often the data will be backed up, to which locations, and how many copies will be made; b) who is responsible for data backup; and, c) state the approximate amount of storage needed for the data and whether available storage is sufficient.*
33. Outline how the data will be recovered in the event of an incident (required). *Note: Be sure to include the following details: a) what are the main data security risks and how they will be managed, including whether any institutional data security policies are in place? b) identify any formal standards that you will comply with; and, c) list relevant funder, institutional, departmental, or group policies on data management, data sharing, and data security.*
34. State the main risks to data security and describe how these will be managed to keep the data secure (required).
35. If creating or collecting data in the field, outline how will you ensure its safe transfer into your main secured system (required).
36. Describe how you will ensure that collaborators can access your data securely (required).

Selection and Preservation

37. List data that are of long-term value and should be retained, shared, and/or preserved; with an estimated retention time (required).
38. List any data that must be retained/destroyed for contractual, legal, or regulatory purposes (required). *Note: Consider the foreseeable research uses for the data (e.g., to validate your research findings, conduct new studies, or for teaching).*
39. Provide an explanation of how the decision to keep data was/will be made (required).
40. State the long-term preservation plan for the dataset (required). *Note: If using a repository, state where the data will be stored (repository name and URL), relevant repository policies and procedures, how requirements will be met, and if specific fields are required. An international list of data repositories is available via re3data and some universities or publishers provide lists of recommendation (e.g., PLOS ONE recommended repositories). If you are not using a repository*

provide location and file structure and path and resources for long-term data curation.

41. Outline the steps that will be taken to prepare and document the data for sharing and archiving (required).
42. Provide an estimate of resources (e.g., time, effort, costs) required for data preparation (required). *Note: Examples of resources include storage costs, hardware, staff time, costs of preparing data for deposit, and repository charges*.
43. Outline any relevant technical expertise, support, and training that is likely to be required and how it will be acquired (required).

Sharing

44. Outline the plans for data sharing and preservation (if different from above). State where the data will be shared (required). *Note: The methods used to share data will be dependent on a number of factors such as the type, size, complexity and sensitivity of data. State data access and sharing conditions. If you need to restrict access to certain communities or apply data sharing agreements, explain why. If data will be shared in a repository provide the repository name and URL and associated information (resources required, etc).*
45. State when the data will be available (required).
46. Outline how you will ensure potential users can find out about your data. List persistent identifiers you will use for the data (required).
47. List any restrictions on data sharing (required). *Note: Restrictions may be due to confidentiality, lack of consent agreements or IPR, for example. Consider whether a non-disclosure agreement would give sufficient protection for confidential data. Outline possible measures to overcome or minimize expected difficulties.*
48. State whether a data sharing agreement is required. Explain why or why not (required).

Responsibilities and Resources

49. Identify who is responsible for data management (i.e., implementing the DMP, and ensuring it is reviewed and revised) (required).
50. Outline the roles and responsibilities for all data management activities (e.g., data capture, metadata production, data quality, storage and backup, data archiving and data sharing). Identify who is assigned to each role (required). *Note: If this is a collaborative research project, describe how responsibilities be split across partner sites.*

51. State whether data ownership and responsibilities for research data management are part of any consortium agreement or contract agreed between partners (required).
52. List any other relevant funder, institutional, departmental, or group policies on data management, data sharing, and data security (required).
53. Outline and justify any dedicated resources needed to deliver the plan (required). Note: *Examples of resources include software or hardware which is additional or exceptional to existing provision; technical expertise or staff training; data repository charges.*

Appendix C: Sentinel Site Sensors by Location

Table 1: Sensor attributes for the Grass weather station (MET).

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Grass weather station (MET)	2000	2001	Air Temperature	C
	2000	2002	Relative Humidity	%
	2000	2003	Average Wind Speed	m/s
	2000	2004	Maximum Wind Speed	m/s
	2000	2005	Wind Direction	degrees
	2000	2006	Average Wind Speed	m/s
	2000	2007	Maximum Wind Speed	m/s
	2000	2008	Wind Direction 2D	degrees
	2000	2009	Solar Radiation Average	kW/m^2
	2000	2010	Total Solar Radiation	MJ/m^2
	2000	2011	Precipitation Increment	inches
	2000	2012	Precipitation Accumulation	inches
	2000	2013	Barometric Pressure	mm of Hg
	2000	2014	Leaf Wetness	mV
	2000	2015	Soil Water Content 15cm	%
	2000	2016	Soil Water Content 30cm	%
	2000	2017	Soil Water Content 56cm	%
	2000	2018	Soil Water Content 91cm	%
	2000	2019	Soil Temperature 15cm	psi
	2000	2020	Soil Temperature 30cm	psi
	2000	2021	Soil Temperature 56cm	psi
	2000	2022	Soil Temperature 91cm	psi
	2000	2023	Soil Matric Potential 15cm	C
	2000	2024	Soil Matric Potential 30cm	C
	2000	2025	Soil Matric Potential 56cm	C
	2000	2026	Soil Matric Potential 91cm	C
	2000	2027	Battery Voltage	volts

Table 2: Sensor attributes for the Oak Soil Moisture site.

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Oak soil moisture	2100	2101	Soil Water Content 5cm	%
	2100	2102	Soil Water Content 20cm	%
	2100	2103	Soil Water Content 46cm	%
	2100	2104	Soil Water Content 66cm	%
	2100	2105	Soil Matric Potential 5cm	psi
	2100	2106	Soil Matric Potential 20cm	psi
	2100	2107	Soil Matric Potential 46cm	psi
	2100	2108	Soil Matric Potential 66cm	psi
	2100	2109	Soil Temperature 5cm	C
	2100	2110	Soil Temperature 20cm	C
	2100	2111	Soil Temperature 46cm	C
	2100	2112	Soil Temperature 66cm	C
	2100	2113	Battery Voltage	volts

Table 3: Sensor attributes for Redwood weather station (MET).

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Redwood MET	2200	2201	Air Temperature	C
	2200	2202	Relative Humidity	%
	2200	2203	Average Wind Speed	m/s
	2200	2204	Maximum Wind Speed	m/s
	2200	2205	Wind Direction	degrees
	2200	2206	Precipitation Increment	inches
	2200	2207	Precipitation Accumulation	inches
	2200	2208	Leaf Wetness	mV
	2200	2209	Soil Water Content 15cm	%
	2200	2210	Soil Water Content 30cm	%
	2200	2211	Soil Water Content 50cm	%
	2200	2212	Soil Water Content 100cm	%
	2200	2213	Soil Electrical Conductivity 15cm	dS/m
	2200	2214	Soil Electrical Conductivity 30cm	dS/m
	2200	2215	Soil Electrical Conductivity 50cm	dS/m
	2200	2216	Soil Electrical Conductivity 100cm	dS/m
	2200	2217	Soil Temperature 15cm	C
	2200	2218	Soil Temperature 30cm	C
	2200	2219	Soil Temperature 50cm	C
	2200	2220	Soil Temperature 100cm	C
	2200	2221	Battery Voltage	volts

Table 4: Sensor attributes for the Roger's weather station (MET).

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Roger's MET	2300	2301	Air Temperature	C
	2300	2302	Relative Humidity	%
	2300	2303	Average Wind Speed	m/s
	2300	2304	Maximum Wind Speed	m/s
	2300	2305	Wind Direction	degrees
	2300	2306	Precipitation Increment	inches
	2300	2307	Precipitation Accumulation	inches
	2300	2308	Leaf Wetness	mV
	2300	2309	Soil Water Content 15cm	%
	2300	2310	Soil Water Content 30cm	%
	2300	2311	Soil Water Content 50cm	%
	2300	2312	Soil Water Content 100cm	%
	2300	2313	Soil Electrical Conductivity 15cm	dS/m
	2300	2314	Soil Electrical Conductivity 30cm	dS/m
	2300	2315	Soil Electrical Conductivity 50cm	dS/m
	2300	2316	Soil Electrical Conductivity 100cm	dS/m
	2300	2317	Soil Temperature 15cm	C
	2300	2318	Soil Temperature 30cm	C
	2300	2319	Soil Temperature 50cm	C
	2300	2320	Soil Temperature 100cm	C
	2300	2321	Battery Voltage	volts

Table 5: Sensor attributes for Upper Martin weather station (MET).

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Upper Martin MET	2400	2401	Air Temperature	C
	2400	2402	Relative Humidity	%
	2400	2403	Average Wind Speed	m/s
	2400	2404	Maximum Wind Speed	m/s
	2400	2405	Wind Direction	degrees
	2400	2406	Precipitation Increment	inches
	2400	2407	Precipitation Accumulation	inches
	2400	2408	Leaf Wetness	mV
	2400	2409	Soil Water Content 15cm	%
	2400	2410	Soil Water Content 30cm	%
	2400	2411	Soil Water Content 50cm	%
	2400	2412	Soil Water Content 100cm	%
	2400	2413	Soil Electrical Conductivity 15cm	dS/m
	2400	2414	Soil Electrical Conductivity 30cm	dS/m
	2400	2415	Soil Electrical Conductivity 50cm	dS/m
	2400	2416	Soil Electrical Conductivity 100cm	dS/m
	2400	2417	Soil Temperature 15cm	C
	2400	2418	Soil Temperature 30cm	C
	2400	2419	Soil Temperature 50cm	C
	2400	2420	Soil Temperature 100cm	C
	2400	2421	Fuel Moisture	%
	2400	2422	Fuel Temperature	C
	2400	2423	Battery Voltage	volts

Table 6: Sensor attributes for the Lower Martin weather station (MET).

Location	***Site ID***	***Sensor ID***	***Sensor***	***Units***
Lower Martin MET	2500	1601	Air Temperature	C
	2500	1602	Relative Humidity	%
	2500	1603	Average Wind Speed	m/s
	2500	1604	Maximum Wind Speed	m/s
	2500	1605	Wind Direction	degrees
	2500	1606	Precipitation Increment	inches
	2500	1607	Precipitation Accumulation	inches
	2500	1608	Leaf Wetness	mV
	2500	1609	Soil Water Content 15cm	%
	2500	1610	Soil Water Content 30cm	%
	2500	1611	Soil Water Content 50cm	%
	2500	1612	Soil Water Content 100cm	%
	2500	1613	Soil Electrical Conductivity 15cm	dS/m
	2500	1614	Soil Electrical Conductivity 30cm	dS/m
	2500	1615	Soil Electrical Conductivity 50cm	dS/m
	2500	1616	Soil Electrical Conductivity 100cm	dS/m
	2500	1617	Soil Temperature 15cm	C
	2500	1618	Soil Temperature 30cm	C
	2500	1619	Soil Temperature 50cm	C
	2500	1620	Soil Temperature 100cm	C
	2500	1621	Fuel Moisture	%
	2500	1622	Fuel Temperature	C
	2500	1623	Battery Voltage	volts

Table 7: Sensor attributes for the 222 sensors that are being installed at 17 long-term vegetation research plots.

Location	*Sensor*	*Units*
Micro-MET stations: Installing 17 stations paired with vegetation research sites	Air Temperature	C
	Relative Humidity	%
	Leaf Wetness	mV
	Soil Water Content 15cm	%
	Soil Water Content 30cm	%
	Soil Water Content 50cm	%
	Soil Electrical Conductivity 15cm	dS/m
	Soil Electrical Conductivity 30cm	dS/m
	Soil Electrical Conductivity 50cm	dS/m
	Soil Temperature 15cm	C
	Soil Temperature 30cm	C
	Soil Temperature 50cm	C

Table 8: Stream flow and stage sensors with manual data collection

Location	*Site ID*	*Sensor ID*	*Sensor*	*Units*
Secondary Roger's Creek stream transducer	2700	2701	Hydrostatic Pressure	psi
	2700	2702	Temperature	C
	2700	2703	Water Depth	feet
Primary Roger's Creek Transducer	2800	2801	Hydrostatic Pressure	psi
	2800	2802	Temperature	C
	2800	2803	Water Depth	feet
Porter Creek flow onset	3000	3001	Channel Temperature	C
	3000	3002	Bank Temperature	C
Rogers Creek flow onset	3100	3101	Channel Temperature	C
	3100	3102	Bank Temperature	C
Martin Creek flow onset	3200	3201	Channel Temperature	C
	3200	3202	Bank Temperature	C
Weimar Creek flow onset	3300	3301	Channel Temperature	C
	3300	3302	Bank Temperature	C
	3300	3300	Mid Bank Temperarture	C
Redwood Creek flow onset	3400	3401	Channel Temperature	C
	3400	3402	Bank Temperature	C

Appendix D: Sentinel Site Field Station Background

The vision for Pepperwood specifically as a Sentinel Site monitoring station was launched by the Pepperwood Foundation in collaboration with the Terrestrial Biodiversity and Climate Change Collaborative (TBC3) in 2010, yet it builds on preliminary investigations on the part of the California Academy of Sciences during its tenure as Pepperwood's steward (1978 to 2005). A critical biological baseline for the Sentinel Site is our herbarium collection formed over the period from 1980 to 1992 by the Academy's resident biologist, Greg deNevers. In 2001, California Academy of Sciences Collections Manager Moe Flannery initiated a breeding bird survey transect at Pepperwood following the Point Blue and California Avian Data Center protocols. California Academy of Sciences entomologist Brian Fisher regularly conducts ant surveys at the preserve as part of a training course, and has also preserved records of specimens and observations.

The Pepperwood Foundation's first Sentinel Site initiative was the 2010 installation of a weather station, thanks to a generous donation of equipment from the USGS and time by Pepperwood citizen scientist Dave Andersen. Between 2010 and today the Sentinel Site has expanded somewhat opportunistically via grant-based and visiting scholar driven opportunities to augment the watershed sensor network and expand monitoring of biological indicators. A major period of growth from 2010-2016 was thanks to Gordon and Betty Moore Foundation support of Pepperwood's Terrestrial Biodiversity and Climate Change Collaborative (TBC3.org). Many of these efforts may be considered pilot studies which are now under evaluation in this plan for potential inclusion in our long-term monitoring strategy.

Process for selecting Sentinel Site monitoring protocols, locations, and pilot projects
The process we undertook to determine what, where, and how to monitor physical or biological characteristics was done in collaboration with affiliate scientists and technical advisors in all of the steps below-with substantive support in particular from the Pepperwood-based Terrestrial Biodiversity Climate Change Collaborative (TBC3).

Key questions include the following.

- Is the feature present and significant at our site?
- Is there peer-reviewed research to suggest it is a good indicator, and if so, an indicator of what?
- Are others in the scientific community measuring this, and in particular at comparable sites such that it will inform queries at larger scales?

Pepperwood's preliminary priorities for instrumenting the Sentinel Site have been installation of weather and hydrology measurements to complement existing plant and bird surveys, and to expand biological monitoring to capture trends in plant phenology, woodland and grassland community dynamics, and mammalian wildlife.

Siting considerations include whether you are seeking "representation" of a site, perhaps central tendencies or average values, versus seeking to measure the range or diversity of conditions across a site, or versus seeking a truly "random" sample. In general, site considerations require analyzing site variability in terms of both physical and biotic factors. Options include stratifying across landscape categories, co-locating companion measurements, or selecting sites that reduce the complexity of processes being measured (for example, locating weather stations in open locations to minimize interference via canopy, etc). At times, there may only be very limited locations where measurements can occur-such as stream flow monitoring on a site dominated by ephemeral streams, or a very restricted habitat, like serpentine soils, that host rare species.

At Pepperwood we have established a set of reference automated weather stations that provide measurements for the different topo-climate zones across the entire preserve, yet we have labor-intensive hydrology measurements in only a subset of preserve watersheds. Most biological measurements utilize stratified plots, transects, or grid arrays either randomly placed or based on vegetation community (which we use to define habitat "types" and management units).

No matter how well-documented or field-tested a protocol may be, the first season or year of monitoring may need to be considered a "pilot project" or a "beta test." The best case scenario is to have an expert coach your team in the field on set up, but this is not always feasible. In some cases with a new sensor or process, it may make sense to make a smaller deployment than is ultimately desired. Evaluating the results of your pilot project with a team allows for refinement of protocols and a better understanding of the time commitment and equipment required. Then good project planning documentation is needed to support a successful sustained effort. Pepperwood has boot-strapped several of its monitoring pilots, sometimes building on opportunistic developments in researcher, student, or citizen science interest, or the availability of donated equipment. We have to balance the addition or expansion of projects with the very limited staff time available. We will take a more targeted and structured approach to pilot projects moving forward, yet maintain the flexibility to capitalize on opportunities as they arise.

Pepperwood's Data Management Strategy (Appendix B) outlines basic principles and practices for managing Pepperwood Sentinel Site data including visiting scholar data and data collected on implementation and evaluation of ecological management. This strategy addresses the diversity of data and materials, standards formats and metadata, roles and responsibilities, dissemination methods and destinations, policies for data sharing, public access, storage, and preservation of data.

On a day-to-day basis, datasets are managed and archived in functional units, either by sensor cluster or individual project, which form the unit of data collection and management. Each Sentinel Site project will complete a Data Management Plan (outlined in Appendix B). The generation of standardized metadata and DMPs with visiting scholars will help ensure effective data quality control, archiving and security, timely analysis, and appropriate sharing to ensure application to effective conservation outcomes.

Options for reporting Sentinel Site results include the following, and will be customized for key datasets and products on a case-by-case basis.

- Direct delivery to data platforms dedicated to hosting specific data types or protocols
- Internal Pepperwood working reports and data visualizations to guide project management and sampling design
- Pepperwood "white paper" technical reports-self-published and disseminated
- External collaborator/visiting scholar agency reports (i.e. USGS report on soil moisture)
- Posters and presentations at scientific and other conferences
- Peer-reviewed publications
- Social media, including Pepperwood website and blog, partner websites, facebook, and twitter