Eel River Critical Zone Observatory

Year 4 Annual Report
June 2017

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A. Accomplishments

1. What are the major goals of the project?

The major goals of the Eel River CZO as outlined in our Management plan are to answer these four questions:

1. Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments?
2. How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?
3. What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?
4. Will changes in critical zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?

Additionally, we propose to develop a numerical platform – the Atmosphere-Watershed-Ecology-Stream and-Ocean Model (AWESOM) to synthesize findings from smaller scale studies, couple the different critical zone subsystems together, and explore the long-term and large-scale consequences of the dynamics of the critical zone in the context of changes in climate, land use, and water management policy.

2. What was accomplished under these goals?

a. Major activities:

Question 1: Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments?

<u>1) Vadose Zone Monitoring System and sampling campaigns</u>

A vadose zone monitoring system (VMS) was installed at Rivendell in 2015 that enables sampling at 10 “matrix” sampling ports spaced at 1.5 m intervals in the upper 16 m, and 10 “fracture” sampling ports spaced at 1.75 m intervals in the upper 18 m. Samples are also collected from 12 groundwater wells, 2 lysimeters located in soil, Elder Creek, and some Elder Creek tributaries. As of May 2017, 37 water sampling campaigns have been conducted at Rivendell, with a total of 1002 cation samples, 1005 anion samples, 913 stable isotope (O and H), and 230 dissolved organic/inorganic carbon and total nitrogen samples collected. Analysis is ongoing, though 400 major and trace cation, 380 anion, 788 stable isotope, and 92 DOC/DIC and total nitrogen samples have been analyzed thus far. For each water sample collected, dissolved oxygen, temperature, alkalinity, and pH are measured in the field. Additionally nitrate, ammonium, ferrous iron, and hydrogen sulfide measurements have been made in the field. Cation and anion samples are analyzed at the University of Illinois Urbana Champaign (Druhan), stable isotope samples are analyzed at UC Berkeley (Dawson), and carbon samples are analyzed at the University of Texas at Austin (former student, now Assistant Prof. Daniella Rempe).

At Sagehorn (in mélange), where the thin critical zone is entirely saturated during much of the winter months, water samples are collected from 10 wells, a soil lysimeter, and from Hank and

Dry Creeks. Since May 2017, 12 water sampling campaigns have been conducted at Sagehorn. A total of 188 cation samples, 189 anion samples, 197 stable isotope (O and H), and 28 dissolved organic/inorganic carbon samples have been collected.

2) Downhole geophysics

Regular downhole neutron probe surveys have been conducted at 2 week intervals at Rivendell and 4 week intervals at Sagehorn to track the spatial and temporal dynamics of rock moisture. Additionally, two gamma (nuclear density) surveys have been conducted at Rivendell and two at Sagehorn, and downhole nuclear magnetic resonance surveys have been conducted to quantify the rock moisture (volumetric water content) as well as the size distribution of pores. Samples from the Rivendell field site have been used for laboratory NMR analyses at UT Austin to develop novel, quantitative methods for evaluating rock moisture and the pore size distribution of water filled pores.

3) Ecophysiological investigations

Shoot (stem + leaf) water potential (Ψ) was measured on Oregon white oaks monitored for sap flow on a biweekly to monthly basis during leaf-on, from the end of the 2015 growing season to the end of the 2016 growing season in Sagehorn.

4) Document forces by tree roots at the tree-bedrock interface

Force sensors were installed between tree roots and bedrock at Rivendell, seven on the north facing slope and 3 on the south facing slope. In order to gauge the driving forces from wind, three anemometers were installed in treetops, and accelerometers were installed in tree tops and at base of trees.

Question 2: How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?

1) Vadose Zone Monitoring System (VMS) and campaign sampling of gas concentrations

A round-the-clock sampling campaign was conducted over a 9 day period in January 2017. A total of 517 water samples from Elder Creek, the VMS, and groundwater were collected. Vertical profiles of dissolved oxygen, oxidative-reduction potential and temperature in groundwater have been measured 10 times at Rivendell and 12 times at Sagehorn throughout the year.

Gas sampling ports in the VMS have been used during 9 campaigns at an approximately two-week frequency to measure CO_2 and O_2 concentrations and collect 86 gas samples for d13C analysis (UT Austin). Additionally, 92 water samples from matrix and fracture samplers in the VMS and groundwater have been analyzed for dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) (UT Austin). The co-located measurements of gas concentrations measured in the field, rock moisture content, DIC, DOC, and d13C are being used to parameterize and constrain a reactive transport model developed by Druhan (UIUC).

2) Metagenomics, rhizospheric sampling, and analysis for microorganisms carrying nutrient turnover functions

Metagenomic DNA samples were analyzed from soils in various microenvironments of the CZO. Metagenomic DNA samples from a methanol incubation experiment as well as environmental samples that were collected in summer 2016 at Rivendell and Sagehorn have also been processed and assembled. Samples in the rhizosphere of Douglas Fir trees were collected to conduct a genome-resolved metagenomic analysis of samples.

To identify microorganisms carrying relevant functions for nutrient turnover, genome-resolved metagenomics coupled with proteomics have been applied to samples.

Question 3: What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?

<u>1) Comparative analysis</u>

Comparison of field surveys of wetted channels and spring locations for 2012, 2014 and 2015 were completed. Winter wetted channels were noted during an intense storm period in January 2017 at both Rivendell and Sagehorn (mélange).

<u>2) Model development</u>

A model has been developed that predicts how stream flow is controlled by critical zone thickness and storage capacity.

Question 4: Will changes in critical zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?

<u>1) Food web structure surveys</u>

Three "Eyes on the Eel" 4-day surveys (June, July, Sept of 2016) were conducted to document food web structure at 8 sites down the South Fork Eel and lower Eel mainstem to test patterns against predictions from ERCZO models.

<u>2) Steelhead foraging</u>

Seasonal changes in benthic invertebrate drift, stream hydraulics, water temperature, and juvenile steelhead foraging characteristics were collected in seven riffle-pool units in Elder Creek, a tributary of the South Fork Eel River.

<u>3) Experiments on cyanobacteria dispersal</u>

In summer 2016, experiments on cyanobacterial buoyancy were conducted in order to understand how floating and sinking of cyanobacteria affect their dispersal to sites of human exposure. Cyanotoxin accumulation in benthic macroinvertebrates was measured to understand if cyanotoxins could travel up the aquatic food web.

<u>4) Quantifying stream thermal regimes, and controls on invasive fish species and disease</u>

In the summer of 2016, high-resolution temperature arrays were installed at two cold water tributaries that enter the seasonally warm South Fork Eel. A computer model has been developed that predicts local stream temperature conditions at tributary refugia.

The occurrence of black spot disease in steelhead was documented under varying stream temperature conditions. Field surveys were conducted to quantify the influence of stream flow and temperature on invasive species advance upstream, and growth rate of native species.

Question 5: AWESOM: The Atmosphere-Watershed-Ecology-Stream and-Ocean Model

1) Field investigation of the boundary layer

Sap flow, soil moisture, and local meteorological measurements were initiated around 8 madrone trees on south facing slopes to document key observations needed to advance theory.

2) Model development

a) A 1-D model was developed (intended for use in climate models) to explore the subsurface factors that may sustain evapotranspiration through the dry season.

b) A coupled flow and stream temperature model for the South Fork Eel River was developed.

b. Specific Objectives

Milestone 1: Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments?
1.1 Monitor vadose zone moisture dynamics
1.2 Conduct tree survey at two field sites
1.3 Evaluate water potential in trees with pressure chambers and psychrometers
1.4 Continue instrumentation of trees with force sensors
1.5 Develop and parameterize numerical model of root forces and bedrock-to-soil conversion

Milestone 2: How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?
2.1 Continue microbial genome analyses of sequenced soil
2.2 Begin analysis of microbial genomes of populations in weathered bedrock
2.3 Collect soil samples for metagenomics and metatranscriptomics to link tree physiology to microbial activity and trace gas production
2.4 Collect fungal hyphae for DNA extraction and sequencing to reconstruct fungal genomes
2.5 Continue periodic sampling of gas weathered bedrock
2.6 Collect and analyze VMS samples at Rivendell, and rainfall and runoff samples from Sagehorn and Rivendell

Milestone 3: What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?
3.1 Analyze wetted channel extent for Sagehorn and Rivendell
3.2 Develop semi-distributed hydrologic model

Milestone 4: Will changes in critical zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?

4.1 Investigate relationships among river food webs, stream flows, and juvenile salmon
4.2 Continue assessment of cyanotoxin bioaccumulation in macroinvertebrates and cyanobacterial dispersal dynamics

4.3 Conduct longitudinal surveys for salmonid genetic samples
4.4 Collect water temperature data using UAVs
4.5 Continue development of idealized 3D refugia model
4.6 Begin experimental assessment of influence of temperature on growth of the California Roach
4.7 Conduct repeat surveys along South Fork and mainstem Eel at tributary junctions of habitat, insects, algae, and fish abundance

Milestone 5: Synthesis Modeling (the Atmosphere-Watershed-Ecology- Stream-Ocean Model)
5.1 Adapt existing plant-soil-atmospheric model to Angelo/Sagehorn plant community
5.2 Couple model to a saturated water module and stable isotopic analysis
5.3 Explore coupling 1D vadose zone and groundwater model to Community Land Model

c. Significant results: (Numbers correspond to 'Specific objectives' above)

1.1 Analysis of VMS data indicate that during periods of peak transpiration, rock moisture at 4-6 m is at a maximum, suggesting that rock moisture is a key source of water to vegetation across the site. The continuous record reveals that even during discrete storm events, little to no transient rock moisture storage occurs at depth, indicating deep passage of water via isolated fracture systems. The vertical structure revealed by both continuous moisture monitoring via the VMS and discrete neutron probe surveys provides direct evidence for the correspondence between water uptake by vegetation and rock properties.

1.2 ongoing- no significant results

1.3 In spite of high vapor pressure deficits and declining pre-dawn water potentials (to below -3.0 MPa), we observed mature Oregon white oak trees maintaining high rates of sapflow. Sapflow continued due to an anisohydric water use strategy in which a roughly constant pre-dawn to mid-day gradient in Ψ was maintained throughout the season (≈1.6 MPa). Daily depletion and recharge of stored water in stem tissue and leaves sustained transpiration. Leaves experienced low Ψ (below -4 MPa) and declining hydraulic conductance, yet remained functional. Pressure-volume curve analyses revealed that the maintenance of positive turgor pressures at low Ψ may be attributable to dynamic cell wall elasticity adjustment.

These observations demonstrate that *Q. garryana (Oregon white Oak)* is extremely drought tolerant as compared to Douglas Fir, explains why it survives in the thin critical zone of the mélange, and improves parameterization of land-plant-atmosphere interaction models.

1.4 Initial results of monitoring tree-driven forces at the tree-bedrock boundary indicate that the style and magnitude of root-driven forces may depend on individual species, size distribution, forest structure, and regional wind patterns. In addition, small diurnal root pressure fluctuations due to water/ sap flow may be enough to weaken enfolding rock due to the sheer number of shrink-swell cycles.

1.5 on-going, no significant results

2.1 Roughly 900 near-complete soil microbial genomes have been assembled from 60 metagenomic samples. Within these genomes between 2-3 highly novel lineages, including a possible new phylum of Bacteria as well as a new phylum of Archaea, have been identified. Additionally, these observations have greatly expanded the number of sequenced genomes for highly relevant soil microbes with few current available genomes including Acidobacteria, Rokubacteria, and Gemmanimonedetes. Highly abundant microorganisms that encode climate relevant metabolic functions not known to occur in any other members of their phyla have been identified.

2.2 on going, no significant results

2.3 on going, no significant results

2.4 on going, no significant results

2.5 see 2.d "key outcomes" below

3.1 Further analysis confirms that summer wetted channel density (and thus water supply and ecosystems) strongly depends on critical zone structure. In the Coastal Belt argillites and sandstone, groundwater storage in the thick critical zone slowly drains, sustaining summer-wetted channels. Springs, fixed in location, controlled the extent of flow. Identical total catchment wetted channel drainage densities (the summed lengths of all wetted channels within a watershed, divided by the area) of 1.94 km/km^2 in early summer and 1.44 km/km^2 in late summer were found in the two adjacent watersheds in the Coastal belt. In contrast, in the thin critical zone on the mélange, the small seasonal storage drained and the channels were dry by May.

3.2 A semi-distributed model, now developed, demonstrates how the thickness of critical zones influences peak and summer low flows. It highlights the need to be able to predict critical zone thickness (and hydrologic properties) across landscapes.

4.1 on going, no significant results

4.2 on-going, no significant results

4.3 samples collected, analysis on going, no significant results

4.4 UAS (unmanned aerial system) flights were conducted at two heavily-instrumented sites of the South Fork Eel River and found that the UAS measured stream temperatures deviate from *in situ* sensor-measured temperatures by an average of one degree. The UAS is, however, better suited to detect fine-scale variabilities in stream thermal patterns and gradients. This fieldwork was followed up with a modeling study that found the UAS is best equipped to detect groundwater inputs in small but deep streams with low flow, where reduced turbulent mixing preserves cold water signatures upon interaction with the overlying stream water.

4.5 We've developed an idealized computational fluid dynamics model using OpenFoam that describes cold water refugia at the confluences in the South Fork of the Eel River. With the idealized confluence model we have come up with scaling relationships between different flow conditions, fluvial geomorphology, and temperature regimes and the extent and persistence of cold water refugia at confluences.

4.6 Experiments show that the introduced California roach have significantly higher growth rates in warmer conditions and suggest that the fish could potentially reach the size of sexually maturity, in the year they hatch, greatly increasing population growth rate and their dominance in the ecosystem.

4.7 on-going, no significant results

5.1 on-going, no significant results

5.2 on-going, no significant results

5.3 Model simulations indicate that the amount of subsurface moisture remaining at the end of the wet winter is determined by the competition among abundant precipitation input, fast infiltration, and winter ET (evapotranspiration) demand. The weathered bedrock retains ~30% of the winter rain and provides a substantial moisture reservoir that may sustain ET of deep-rooted (>8 m) trees through the dry season. From the results, the question can be asked: given a tree species whose ET magnitude and seasonality are known approximately, what root characteristics are needed to survive in this precipitation and geologic setting? The model indicates that actual ET in a Mediterranean climate nearly doubles when the maximum rooting depth is increased from 3 to 10 m. For trees with 10 m roots, it is the roots below 4 m, comprising 10% of the root mass, that access moisture in the weathered bedrock to sustain summer ET. A small negative feedback exists in the root zone, where the depletion of moisture by ET decreases hydraulic conductivity and enhances the retention of moisture. Hence, hydraulic redistribution by plant roots is impactful in a dry season, or with a less conductive subsurface.

d. Key outcomes or other achievements:

The challenge of the deep vadose zone in weathered bedrock

Our 2015 and 2016 Annual Reports described, respectively, the discovery and importance of *rock moisture*, and the startling difference in hydrologic dynamics in deep and shallow critical zone dominated landscapes (*water-store* versus *water-shed*). These and other findings led us to, literally, dig deeper. In Fall 2015 we installed the Vadose Zone Monitoring System (VMS) and have been aggressively sampling since. The work has demonstrated both the great value of identifying a way to sample the unsampled zone of the critical zone (i.e. the deep vadose zone in weathered bedrock) and the importance of a sustained and frequent sampling program.

The VMS consists of two 19 m long holes, drilled along contour (normal to the downhill direction) at 55 degree angles relative to the horizontal (leading to the lowest position of the hole being 16 m below the surface). Each hole is filled with a sleeve mounted on the outside with sampling intakes and monitoring instruments and infilled with cement (causing a tight seal against the outer wall of the hole). Along one sleeve ("A") at 10 positions distributed at nearly even intervals over the 16 m of vertical decent are the following : 1) a time domain transmissivity instrument (to monitor rock moisture dynamics), 2) a temperature probe, 3) a pressure transducer, and 4) electrical conductivity sensor. At each of the ten intervals, porous cups embedded within 25 cm long silica pillows serve as lysimeters to collect water. The second sleeve (“B”) has ten 1.5 long sampling ports (designed to capture fracture flow) and near these ports are perforated sampling tubes used to extract gas. We now have collected over 600 samples from the VMS system, based on nearly biweekly sampling since October 2015.

Our Oshun et al. (2015) paper used stable isotopes of rain and groundwater to infer that in the thick vadose zone, the incoming rain mixed with prior waters until a threshold moisture rise led to significant water displacement to the groundwater, by which time the input isotopic signal was well-mixed. The resulting groundwater stable isotopic signal is nearly invariant in time. Based on extensive sampling of isotopes in trees, soil and weathered bedrock, Oshun also concluded that Douglas fir relied on rock moisture as a water source while the broad leaf trees relied mostly on soil water. Kim et al. (2014; 2017) concluded that water passing through the vadose zone likely experienced rapid solute evolution through reaction with carbonic acid and that deepest groundwater slowly released to the channel in late summer was the most chemically evolved. These inferences by Kim et al., particularly the rapid chemical evolution in the vadose zone, explain the low variation in solute concentrations with orders of magnitude changes in stream flow in our study watershed.

Data from the monitoring and sampling of the VMS system are actively being analyzed, but initial observations support some interpretations and raise new fundamental questions. At the end of the long dry season, we were able to collect water samples from the lysimeters for all but the shallow ports, which were too dry to sample. Our preliminary analysis of the high temporal resolution VMS data now reveal that in the upper part of the vadose zone, individual storm isotopic signals can penetrate to at least 6 m below the surface before being damped out. The stable isotope concentrations systematically change with depth to about 6 to 8 m below the surface, below which concentrations are nearly the same as the mean rainfall and the groundwater. Hence, we directly document that the vadose zone does retain and mix incoming rainfall, damping out the isotopic signal to the groundwater, as hypothesized by Oshun et al. Furthermore we detect elevated solute concentrations in the shallow rock moisture in the vadose zone, consistent with our hypothesis of rapid cation exchange driven by carbonic acid in the clay-rich weathered saprolite, linking rock properties and weathering processes directly to water chemistry.

Discrete geophysical surveys and continuous monitoring with the VMS reveal that rock moisture is dynamic (declining in summer, increasing in response to winter rains) to a depth of about 12 m. The summer decline must be going to transpiration, yet the stable isotopes of the vadose zone and of the trees simply don’t match. None of the Douglas fir samples are similar to the vadose zone values and few of the broad leaf trees (oaks and madrones) match. Our observations and recent studies by others are now causing the community to reassess the assumptions that there is no subsurface isotopic fractionation and that trees faithfully record their water sources. This is a major methodological issue that is essential to understanding the links among critical zone properties, water sources, vegetation, climate, and ecosystem resilience.

Our initial VMS observations also shed light on how dense, low permeability shale gains porosity, stores incoming rainwater in fractures, and develops a perched groundwater that drains to channels. Geochemical sampling in the VMS along with high temporal resolution vertical profiles of dissolved oxygen in the groundwater indicate that oxidative weathering reactions are responsible for porosity development. Methane, O_2 and CO_2 profiles are sampled through the VMS system. Our collaborators Rempe and Druhan are now using the VMS dataset and a reactive transport model to develop process based links between weathering, hydrology, and landscape evolution. These collaborators are also introducing additional measurements, such as the use of nuclear magnetic resonance (measurement in well boreholes), to document porosity and pore size distribution, and stable isotopic analysis of carbon to track processes controlling carbon dynamics at depth. International collaborations with the French CZO network are leveraging the high spatial and temporal resolution sampling and rich dataset in the deep bedrock vadose zone to advance isotope tracers in hydrology.

Much work remains in analyzing the VMS data, but it promises to reveal for the first time how the vadose zone evolves and how the development of a deep vadose zone controls moisture availability, storm runoff, stable isotope signals, solute chemistry, and microbially-mediated gas fluxes. In essence, we are moving from hypothesizing about what takes place in the unsampled zone to detailed documentation of processes there. Because many upland landscapes are underlain by meters of weathered rock, the methodology and process-based insights offered by our intensive VMS sampling are readily transferrable to other sites (including the CZO's) and our results suggest that further direct monitoring of the deep, fractured vadose zone is needed to understand water and carbon dynamics and landscape evolution.

3. What opportunities for training and professional development has the project provided for funded personnel?

In the ER CZO post-docs, graduate students and undergraduate typically work with several of our PIs whose expertise range across atmospheric science, tree physiology, geomorphology, microbial ecology, geobiology, hydrology, stream ecology and geochemistry. Geologists and atmospheric scientists work on where trees get their water, microbial ecologists study hydrologic processes and geochemistry, and stream ecologists explore the geomorphic processes that control fish distribution and foodwebs. Students freely interact across four departments, four deans and three colleges. This training will create "critical zone scientists."

During monthly meetings attended by all ER CZO participants, both undergraduate and graduate students present their research and debate findings. These presentations fine tune their speaking skills and sharpen their research efforts. We discuss research findings, future plans and ways to connect the pieces of the critical zone. We subsidize students to attend meetings and work closely with them to prepare them for presentations and to advise them on manuscript preparation. Additionally, many of the CZO graduate students have supervised multiple undergraduates, both in the field and in the laboratory.

The graduate students are forming a group identity and have begun sharing technology and field skills. Students frequently train new students on deployment, operation and data collection from field instruments. The PIs also spend considerable time in the field with graduate students, training them in field methods and developing measurement procedures, and in the laboratory to teach analytical and modeling methods.

4. How have the results been disseminated to communities of interest?

Our CZOMP lists our strategy for engagement with other CZOs – which focused on common questions and measurements and cross-site research. We proposed that several strategies to engage the larger community including publishing papers, presenting findings at meetings, sharing data, and welcoming participation by groups not affiliated with the CZO network

Researchers in the CZO regularly present their findings at conferences, meetings, invited talks, and seminars. In the past year, graduate students, postdocs, and PI's have presented at the American Society for Microbiology Conference, the American Geophysical Union Meeting, the Ecological Society of America Annual Conference, the Society for Freshwater Science Annual Meeting, the Joint Meeting of Ichthyologists and Herpetologists, the Arlington Meeting for Critical Zone Science, Isotopes 2017, and gave many invited talks at universities. Our CZO science was on display at the recent annual meeting of the California-Nevada Chapter of the American Fisheries Society (held in Eureka, California from April 5-7, 2017), where many individuals from the ERCZO presented their research (M. Power, S. Carlson, S. Kelson, P. Georgakakos, T. Wang, and G. Rossi)

In the past year, PI's have given CZO related invited talks/seminars at Caltech (Fung), Harvard U.(Fung), U. of Washington (Carlson), U. of Arizona (Carlson), U. of Montana (Dietrich), Biosphere-2 Earth Day celebration (Dietrich), Beijing Normal University (Dietrich), Cambridge U. (Carlson), UC Santa Cruz (Power), U. of Montana (Power), U. of Oklahoma (Power), and U. of Arkansas (Power).

Engagement by the research community is extensive and continues to grow. In the past year we have collaborated with University of California, Davis (M. Miller) to conduct genetic analyses on *O. mykiss*, Babson College (N. Karst) on the coupled flow-temperature model, the Swedish Institute for Agricultural Sciences (G. Vico) on stochastic hydrologic modeling, UC Berkeley Visiting Scholar S. Kupferberg on amphibian conservation, University of Illinois (J. Druhan) and University of Texas, Austin (D. Rempe) on solute evolution (and reactive transport modeling) through the critical zone, Institut de Physique du Globe de Paris (Bouchez and Gaillardet) on isotope fingerprints of groundwater, Colorado State University (J.T. Minear) on wind-induced forces, San Francisco State University (L. Sklar) on live tree models, Universite de Rennes (M. Bormans) on cyanobacterial flotation, University of California, Santa Cruz (R. Kudela) on cyanobacterial toxicity, The University of Nebraska-Lincoln (C. Detweiler) on the unmanned aerial system project, Humboldt State (Master's student L. Jensen) on developing an invertebrate study in the Eel River, Wuhan University (D. Liu) on hydrologic modeling, The Joint Genome Institute (T. Northen) on metabolomics in soil samples, Oak Ridge National Labs (C. Pan) on proteomics in soil samples, Wright State University (Y. Vadeboncoeur) on algal blooms, and University of Alberta (A. Oliver) on carbon exports from watersheds.

5. Goals during next reporting period

As specified in the CZO reporting guidelines our goals are presented as a graphical timeline.

	2017							2018								
	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Task 1																
Monitor vadose zone moisture dynamics																
Explore controls on stable isotopes in storage reservoirs and trees																
Monitor sap flow, soil moisture and meteorology on Rivendell South facing slope																
Measure and model root forces at the root-bedrock interface																
Task 2																
conduct methanol incubation experiments on soils																
Continue annotation of assembled soil genomes																
Explore genome-resolved analysis of subsurface rhizospheric community																
Continue periodic sampling of gas weathered bedrock																
Collect and analyze VMS samples at Rivendell, and rainfall and runoff samples from Sagehorn and Rivendell																
Task 3																
Develop further the model for critical zone dependent runoff																
Relate concentration- discharge relationships to the extent of wetted channels in Sagehorn																
Task 4																
Document effects of wet and dry years on steelhead																
Continue assessement of cyanotoxin bioaccumulation in macroinvertebrates and cyanobacterial dispersal dynamics																
Continue analysis of cold-water refugia																
Quantify the phenology of food webs in salmon bearing streams																
Document temperature controls on the spread of invasive fish																
Conduct repeat surveys along South Fork and mainstem Eel at tributary junctions of habitat, insects, algae, and fish abundance																
Task 5--AWESOM Model																
Develop further the 1-D vadose zone model based on observations on South slope																
Advance the coupled model for stream flow and temperature																

B. Products

1. Publications

Bouma-Gregson, K., Power, M. E., and M. Bormans. (2017). Rise and fall of toxic benthic freshwater cyanobacteria (Anabaena spp.) in the Eel river: buoyancy and dispersal. Harmful Algae, *in review*

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Vrettas, M. and I. Fung. (2017). Sensitivity of transpiration to subsurface properties: Exploration with a 1-D model. Journal of Advances in Modeling Earth Systems, DOI: 10.1002/2016MS000901

Wymore, A. S., West, N.R., Maher, K., Sullivan, P.L., Harpold, A., Karwan, D., Marshall, J.A., Perdrial, J., Rempe, D.M., and L. Main. (2017). Growing New Generations of International Critical Zone Scientists, Earth Surface Processes and Landforms, *in review*

2. Technologies or Techniques

ERCZO postdoc David Dralle has created a "Recession analyzer" tool, soon to be featured on CUAHSI's online data portal, data.cuahsi.org. Power-law recession analysis uses a simple mathematical model of streamflow recession (the period of time during which streamflows decline between rainfall events) to describe the drainage behavior of watersheds. It is commonly applied for catchment inter-comparison, hydrologic model parameterization, and characterization of riparian aquifers. The Recession Analyzer web-tool links to CUAHSI's hydroshare database, where it can access NWIS streamflow (among other sources) and perform power-law recession analysis. The tool is flexible and can be adjusted to be more/less selective in the extraction of periods of recession, to fit recession curves using both linear and nonlinear regression, and to perform some quantitative "cleaning" of the resulting fitted recession parameter values. This tool will make recession analysis more accessible to scientists or managers less familiar with coding or procurement of streamflow datasets. Work will continue to expand the tool over time to add more complex forms of recession analysis.

3. Inventions, Patent Applications, and Licenses

Nothing to report.

4. Websites

Nothing to report

5. Other Products

Nothing to report

C. Participants

Dietrich, William	PD/PI	3
Bishop, James	Co PD/PI	2
Carlson, Stephanie	Co PD/PI	2
Power, Mary	Co PD/PI	2
Thompson, Sally	Co PD/PI	2
Banfield, Jillian	Faculty	1
Dawson, Todd	Faculty	2
Firestone, Mary	Faculty	1
Fung, Inez	Faculty	1
Chung, Michaella	Postdoctoral (scholar, fellow or other postdoctoral position)	4
Dralle, David	Postdoctoral (scholar, fellow or other postdoctoral position)	12
Marshall, Jill	Postdoctoral (scholar, fellow or other postdoctoral position)	10
Vrettas, Michail	Postdoctoral (scholar, fellow or other postdoctoral position)	2
Hunter, Jennifer	Other Professional	2
Ogle, Virginia	Other Professional	1
Roy, Sarah	Other Professional	2

Baxter, Wendy	Technician	2
Bode, Collin	Technician	10
Cargill, Samantha	Technician	10
Minton, Brandon	Technician	5
Wong, Chris	Technician	6
Wood, Todd	Technician	1
Bilir, T.	Graduate Student (research assistant)	8
Bouma-Gregson, Keith	Graduate Student (research assistant)	8
Fernandez, Nicole	Graduate Student (research assistant)	3
Georgakakos, Philip	Graduate Student (research assistant)	8
Greer, George	Graduate Student (research assistant)	8
Hackett, Caroline	Graduate Student (research assistant)	0
Hahm, William	Graduate Student (research assistant)	8
Kelson, Suzanne	Graduate Student (research assistant)	8
Lee, Shawn	Graduate Student (research assistant)	5
Lovill, Sky	Graduate Student (research assistant)	3
Meek, Katherine	Graduate Student (research assistant)	5

Rempe, Daniella	Graduate Student (research assistant)	3
Rossi, Gabe	Graduate Student (research assistant)	8
Sharrar, Allison	Graduate Student (research assistant)	8
Starr, Evan	Graduate Student (research assistant)	8
Tune, Alison	Graduate Student (research assistant)	5
West, Patrick	Graduate Student (research assistant)	0
Pneh, Shelley	Non-Student Research Assistant	4
Israel, Noah	Undergraduate Student	2
Murphy, Colleen	Undergraduate Student	2
Nelson, Mariel	Undergraduate Student	2
Nuri, Arianna	Undergraduate Student	3
Purcell, Benjamin	Undergraduate Student	4
Schaaf, Cody	Undergraduate Student	2
Schmidt, Logan	Undergraduate Student	0
Tao, Yujia	Undergraduate Student	0
Thiess, C.	Undergraduate Student	0
Wang, Terrance	Undergraduate Student	3

Wang, Yinuo	Undergraduate Student	1
Wang, Jia	Undergraduate Student	4

2. Partner Organizations

Babson College	Academic Institution	Babson Park, MA
Berkeley Natural History Museums	Academic Institution	University of California, Berkeley, CA
Redwood Forest Foundation	Other Nonprofits	Mendocino, CA
San Francisco State University	Academic Institution	San Francisco, CA
Swedish University of Agricultural Sciences	Academic Institution	Sweden
The Nature Conservancy	Other Nonprofits	San Francisco, CA
The University of Texas at Austin	Academic Institution	Austin, TX
University of Alberta	Academic Institution	Edmonton, Alberta, Canada
University of California Natural Reserve System	Academic Institution	Oakland, CA
University of California, Davis	Academic Institution	Davis, CA
University of California, Santa Cruz	Academic Institution	Santa Cruz, CA

University of Grenoble	Academic Institution	Grenoble, France
Colorado State University	Academic Institution	Fort Collins, CO
University of Illinois, Urbana-Champaign	Academic Institution	Urbana-Champaign, IL
University of Nebraska-Lincoln	Academic Institution	Lincoln
University of Wyoming	Academic Institution	Laramie, WY
Université de Rennes 1	Academic Institution	Rennes, France
Virginia Tech	Academic Institution	Blacksburg, VA
Watercourse Engineering, Inc.	Industrial or Commercial Firms	Davis, CA
Wright State University	Academic Institution	Dayton, Ohio
Eel River Recovery Project	Other Nonprofits	Garberville, CA
Friends of the Eel River	Other Nonprofits	Arcata, CA
Humboldt State University	Academic Institution	Arcata, CA
Institut de Physique du Globe de Paris	Academic Institution	Paris, France
Karuk Tribe	Other Organizations (foreign or domestic)	Happy Camp, CA
NOAA National Marine Fisheries	State or Local Government	La Jolla, CA

Service Southwest Region		
Penn State	Academic Institution	State College, PA

3. Other Collaborators

Trent Northen- Collaborator. Lawrence Berkeley National Laboratory. 1 person month worked. Collaborated on metabolomics in soil samples.

Dedi Liu- Collaborator (International), Lawerence Berkeley National Laboratory. 1 person month worked. Fellowship through Wuhan University. Assisted with modeling work.

Blake Suttle- Collaborator, UC Berkeley. 1 person month worked. Examining the factors driving grassland responses to directional shifts in annual climate conditions.

Sarah Kupferberg- Collaborator, UC Berkeley. 1 person month worked. Works on amphibian conservation in California rivers.

D. Impacts

1. What is the impact on the development of the principal discipline(s) of the project?

The critical zone is a "thing" and, as such, a kind of critical zone science discipline is emerging. This was strongly expressed by the young scientists who presented at the NSF Reverse Site Review in November 2016 and at the Critical Zone meeting in Arlington, VA in June 2017. The network of US critical zones is showing the necessity and fruitful consequence of scientists working across traditionally distinct disciplines: geology, atmospheric science, ecology, tree physiology, microbiology and so on. At Berkeley this is expressed not only in the diversity of fields the 9 PIs represent, but in the fact that students freely work across disciplines, departments and colleges to gain deep insight into integrated critical zone processes. Strong expertise in existing disciplines is still essential, but now such expertise can spread and gain new perspectives in a critical zone context.

2. What is the impact on other disciplines?

Berkeley PIs are giving talks at the annual meetings in their disciplines and in invited lectures at universities where they are illustrating how the critical zone matters now to their disciplines. This will help attract others into the intriguing science of the critical zone. The concept of the critical zone as co-evolving entity is now being explored in many disciplines, including hydrology, geomorphology, pedology, geophysics, ecology, and climate science.

3. What is the impact on the development of human resources?

During the past year, 4 post-doctoral researchers, 18 graduate students and 23 undergraduate students conducted research in the ER CZO. Working through the ER CZO has provided these students with invaluable experience in the practical aspects of designing and conducting research projects as well as access to the broad experiences and perspectives of our PIs and senior personnel. Several of the undergraduates will attend graduate school to pursue related research.

Several of our personnel have attained professional positions related to their work at the ER CZO in the last year, including: 1.) Daniella Rempe began an assistant professor position at the University of Texas, Austin in Fall 2016, 2) Jill Marshall will begins an assistant professor position at the University of Arkansas in Fall 2017, and 3) Michail Vrettas began a Data Scientist position at the Central Laser Facility in Oxford, UK in Fall 2016.

4. What is the impact on physical resources that form infrastructure?

Support has enabled a sustained, extensive monitoring system at two remote locations at which all of the instruments are powered by solar panels and most of the data are regularly sent back through the internet to Berkeley. This has created the key infrastructure for research by many of the ERCZO students and post-docs. This year we did much maintenance and added instrumentation for monitoring sap flow, soil moisture and meteorological conditions to the South facing slope of Rivendell.

5. What is the impact on institutional resources that form infrastructure?

The primary field site for the ER CZO is the Heath and Marjorie Angelo Coast Range Reserve (Angelo). Angelo is one of 39 protected natural areas managed by the University of California Natural Reserve System (UCNRS). These areas are maintained by University for the purposes of research, education and public service. Various monitoring apparatuses exist and many of these sites and the UCNRS as recently committed to making near real-time biological, hydrological and meteorological data available to the broader research community.

The UCNRS has provided salary support to ER CZO personnel Chris Wong (field technician), Wendy Baxter (field technician) and Collin Bode (data manager) to establish and maintain a network of weather stations and to create a database structure to enable access to various data streams generated at the UC reserves. This effort is being modeled after the ER

CZO's sensor database, which Virginia Ogle created, and will continue to be supported by UCNRS beyond the lifetime of the ER CZO award.

6. What is the impact on information resources that form infrastructure?

During the 2016-2017 funding period the ER CZO sensor database has been stable. Work has focused on accommodating the partnership with the UCNRS reserves, bringing roughly 300 million more records into the database. The Vadose Monitoring System (VMS) and Sagehorn Ranch weather stations and 3 wells have been incorporated into the realtime system as well.

Cyberinfrastructure improvements

The Eel River CZO has entered into a joint operating agreement with the University of California Natural Reserve System to help manage 38 reserve weather stations. Reserve weather station data are ingested, managed, and hosted by our sensor database and we are providing expertise on the maintenance of their equipment.

Part of this collaboration is a grant to assist in the redesign of our sensor database. Our current system, while very reliable, is 8 years old and has passed the 1 billion record mark and is reaching the limits of a single-server design. The new project, named 'Dendra', after dendritic networks, which sensor observatories resemble, is a modern big data system. The design uses two NoSQL databases (MongoDB, InfluxDB), server-side javascript, and a linearly scaleable cloud architecture. This will allow the system to grow to arbitrarily large sizes without significantly impacting performance or function. The new design is also multi-group from the ground up, which will allow for adoption by other CZO's and organizations if they wish. Both the old and the new systems are specifically for time-series data.

Hydrological Modelers Meeting

In May 2017, co-PI Sally Thompson met with hydrology modelers from the USGS and the State Water Resources Control Board (SWRCB) to share insights, establish connections, and learn about overlapping research efforts within these different organizations.

7. What is the impact on technology transfer?

See "cyberinfrastructure improvements" above.

8. What is the impact on society beyond science and technology?

ER CZO researchers, anchored by Co-I Mary Power, have participated in many outreach efforts. In addition to various speaking engagements and meetings the group has been involved in several long-term collaborative partnerships, some of which are ongoing. ER CZO has strong interactions with the very active citizen's river watch group, the Eel River Recovery Project (ERRP). The ERCZO coordinates and shares data from joint temperature, fish, native frog, invasive snail and crayfish, and algal, cyanobacterial, and cyanotoxin monitoring efforts distributed throughout much of the 9546 km^2 Eel River basin. These riverine biota are supported, or stressed, depending on the nature, timing, and magnitude of delivery of several Critical Zone currencies (water, heat, solutes, and sediments) to channel networks. CZO researchers regularly attend and speak at ERRP watershed meetings, and ERRP members and leaders speak and participate in our short Angelo Reserve courses and workshops.

HHMI video on riverine food webs
Professor Mary Power and graduate student Gabe Rossi participated in a Howard Hughes Medical Institute (HHMI) video effort that focused on Dr. Power's research, titled "Riverine Food Webs – How Flow Rates Affect Biomass." The video is a part of the HHMI BioInteractive video series that showcases scientists at work.

ERRP- cyanotoxin data
Graduate students Keith Bouma-Gregson and Gabe Rossi coordinated volunteers of the ERRP project in the deployment and retrieval of cyanotoxin samplers in the Eel River Watershed. These cyanotoxin data were then shared with the ERRP to assist and enhance their monitoring efforts for cyanobacteria in the watershed.

Community Resources for Science
Graduate student Suzanne Kelson participates in the "Be a Scientist" program led by Community Resources for Science, a local Berkeley non-profit. This program pairs graduate students with groups of middle school students to help them design and conduct their own science projects. Middle schoolers learn about Suzanne's research and the impact of yearly precipitation on freshwater ecology. Students gain an understanding of the highly collaborative nature of science by learning about the CZO's research activities.

Lawrence Hall of Science- video on the Critical Zone ecohydrology
PI Bill Dietrich, graduate student Jesse Hahm, and field technician Samantha Cargill are interviewed in a video showcasing Critical Zone science at Sagehorn and Rivendell study sites of the ERCZO. Kathryn Quigley for the Lawrence Hall of Science at UC Berkeley created the video as part of the educational material provided by the Lawrence Hall of Science.

Article in the Livermore Independent
Graduate student Jesse Hahm was interviewed for a newspaper article with writer Jeff Garberson titled "Complex Research Program Moving Ahead at Livermore Woman's Ranch", published in the Livermore Independent in Sept. 2016. The article describes the CZO research occurring at the Sagehorn-Russell Ranch located in Livermore, CA.

Field trip at Standish-Hickey Recreation Area
Graduate student Phil Georgakakos led a field trip for the public at Standish-Hickey State Recreation Area focused on the identification of river organisms including algae, invertebrates, and fish.

Steelhead and invasive fish
Graduate students Gabe Rossi and Suzanne Kelson are working directly on steelhead populations. Graduate student Phil Georgakakos is doing his dissertation work on an invasive

piscivorous fish, the pikeminnow, that threatens native salmonids and other fishes, particularly in warming rivers. ER CZO Undergraduate Noah Israel is studying the impacts of warming on a native minnow. All of these fish studies are of direct interest for (and have received financial and other types of support from) the California Department of Fish and Wildlife, CalTrout, Friends of the Eel River, and ERRP.

NSF-Sponsored Western Water Workshop, Lake Tahoe August 2016
Mary Power was an invited speaker at the Western Water Workshop subtitled "*Quenching a thirsty west: Integrated scientific knowledge and technological infrastructure to solve water issues in the Western United States***".** Some 40 researchers gathered for two days and discussed water challenges in the face of changing climate and large-scale disturbances, focusing on water pollution, wildfires and droughts (Tyler, S. Chandra, S. and Grant, G., 2017, Management strategies for sustainable western water, EOS, 98, https://doi.org/10.1029/2017EO071701.)

Mattole River meeting
From July 8-10 2016, Mary Power visited the Mattole River Restoration Council meeting to look at their projects studying native grass restoration as a means for conserving water and reducing spread of fire in North Coast forests.

Ecosystems of California book chapter
Mary Power gave a talk on a chapter titled "River Ecosystems of California" for a celebration of new UC publication on Ecosystems of California (Hal Mooney and Erika Zavaleta, eds.) at the Berkeley BioSciences Library.

Eel River Recovery Project Community Outreach March 18, 2017
PI's Mary Power and Bill Dietrich offered public presentations about the ERCZO as part of the "Willits Goes Wild Weekends".

CalTrout Eel River Forum
On June 14, 2017 Mary Power spoke at the CalTrout Eel River Forum: "Experimental studies of impacts of deposited fine sediments on juvenile steelhead". Co-PI Stephanie Carlson and graduate students Suzanne Kelson and Gabe Rossi will also speak at this event.

E. Changes/Problems

1. Changes in approach and reasons for change
   N/A
2. Actual or anticipated problems or delays and actions or plans to resolve them
   N/A
3. Changes that have significant impact on expenditures
   N/A
4. Changes in use or care of human subjects
   N/A
5. Changes in use or care of vertebrate animals
   N/A

6. Changes in use or care of biohazards

N/A

F. Special Reporting Requirements

Metrics

Five milestones and their metric of progress (in color)	Status
Milestone 1. Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments?	
1.1 Compare relative water potential gradients and plant water use on north vs. south facing slopes on mudstones at the Rivendell site.	Monitoring continues
1.2 Compare observations on mudstones with similar data collected on mélange (the Shire- now referred to as Sagehorn).	Sagehorn monitoring on going and comparisons now well-established
1.3 Model moisture storage and transport, evapotranspiration, and other energy balance components for hillslopes under different aspects, lithology, and vegetation.	Base model constructed additional data being collected
Milestone 2: How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?	
2.1 Examine the mobilization, transport and delivery of chemical species from subsurface waters to Elder Creek and then further downstream.	Added VMS with biweekly sampling and significant collaboration with Rempe and Druhan
2.2 Determine temporal dynamics and biotic origin of high CO_2 and other atmospherically reactive gases within the critical zone.	Continue monitoring of CO2 and O2, now including depth profiles using the VMS system
2.3 Characterize the microbial community over time and with depth into the Critical Zone.	Ongoing, analysis of soils and rhizosphere well underway
Milestone 3: What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?	
3.1 Map the extent of wetted channels during summer low flow for varying lithology, topography and precipitation.	Completed surveys, data analysis underway
3.2 Establish a network of runoff and stream temperature monitoring and use that to motivate and test models of water transport and in-stream energy balance.	Network expanded to two mélange watersheds
3.3 Characterize drawdown, flow and temperature oscillations in Russian River using the existing flow gauge network.	Developing analytical framework, field work initiated
3.4 Develop and test models of stream network contraction during summer low flow.	Model now includes critical zone thickness
Milestone 4: Will changes in critical zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?	
4.1 Compare algae and cyanobacteria production at three main-stem South Fork Eel reaches that experience different radiation and flow regimes.	Survey expanded to sites downstream and to mainstem, and to mechanisms of dispersal
4.2 Monitor salmonid performance in two tributaries of the South Fork Eel.	Monitoring expanded to include genetic surveys and thermal controls
4.3 Develop coupled biological-physical models for the study reaches.	Initial model developed. Some additional data now sought
Milestone 5: Synthesis Modeling (the Atmospheric, Watershed, Ecology, Stream, and Ocean Model)	

	5.1 Assemble pre-existing model components.	Model ready to connect to CLM
	5.2 Develop and test models for hillslope scale groundwater recharge and discharge incorporating the effects of preferential fracture flow.	Model developed with intention to like to CLM
	5.3 Develop and test model for species- and lithology-specific water uptake from the critical zone.	Samples collected from both Rivendell and Sagehorn and being analyzed
	5.4 Develop and test models of the diurnal oscillations in flow and stream temperature for entire stream network.	Model developed and mechanisms controlling diurnal oscillations being tested
	5.5 Project from AWESOM the effects of climate and land use change on future critical zone currencies.	Developed plans to link hillslope model to channel network runoff model

CZO Network Activities

1. Participation in CZO network meetings

W.E. Dietrich participates in monthly CZO telecons. He visited the CZO PI gathering at Reynolds Creek CZO in September 2016, and presented a summary of key critical zone findings at the NSF Reverse Site Review meeting in November 2016. The ERCZO will host the PI field meeting September 8-11, 2017.

W. E. Dietrich, J. Hahm, and D. Dralle presented at the CZO network meeting from June 4-6m 2017 in Arlington, VA.

2. CZO Data Managers working group

In response to concerns from both PI's and Data Managers across the CZO network, the Data Managers have formed a working group to discuss management needs and potential centralization of data management systems. ER CZO Data Manager Collin Bode is actively participating in the groups monthly CyberMeetings, where CZO data managers trade information and assist each other.

2. Cross-site collaborations:

a) Post-doc Jill Marshall is working across Boulder, Southern Sierra and Eel River CZOs. She is working to parameterize and calibrate a soil production function for forested landscapes based on observations of the mechanics of root-driven bedrock damage and detachment using observations at each of the CZOs.

b) The ERCZO is collaborating on a CZO wide post-doctoral research project on hydrologic partitioning in the critical zone.

c) The ERCZO is collaborating with the Shales Hill CZO on characterizing weathering induced porosity evolution in shales.

d) The ERCZO hosted Kathleen Lohse, director of the Reynolds Creek CZO, at our May 2017 Monthly CZO Technical Meeting. Dr. Lohse presented recent research updates from Reynolds Creek and learned more about the ERCZO activities and research.

e) The ER CZO has begun a cross-CZO collaboration with the Intensely Managed Landscapes (IML) and Luquillo CZO data managers to develop a cross-CZO query and retrieval web interface. A pilot project is being hosted by IML and is connecting our three data management systems.

3. International CZO Collaborations

The ER CZO hosted Allison Oliver of the University of Alberta. Allison used the Heath and Marjorie Angelo Coast Range Reserve as a site and staging area for her proposed research on watershed exports from across a pacific coastal temperate rainforest gradient. She is investigating carbon exports from watersheds along a North American gradient extending from the Gulf of Alaska, through British Columbia, to Northern California, with Angelo at the southern extreme of this “gradient of ~21 $x10^4$ km^2 that contains the largest contiguous remaining expanse of coastal temperate rainforest in the world. Her work will add to a core mission of the Eel River Critical Zone Observatory—to investigate how water storage, transformation, and release from our forested basins into rivers influence upland-river-coastal ocean linkages. Allison’s work is funded by the Hakai Institute (Calvert Island, BC; www.hakai.org), a member of the Critical Zone Exploration Network, which facilitated this partnership with the Eel River CZO.

ERCZO Director Dietrich was asked to be a collaborator with Professor Xi Chen (Hohai University) on a proposal for work at the Houzhai watershed critical zone observatory, in Puding County, Guizhou Province of southwest China.