ABSTRACTS

Predicting hydrologic, geologic, & biologic responses to a drier and warmer climate in the desert Southwest

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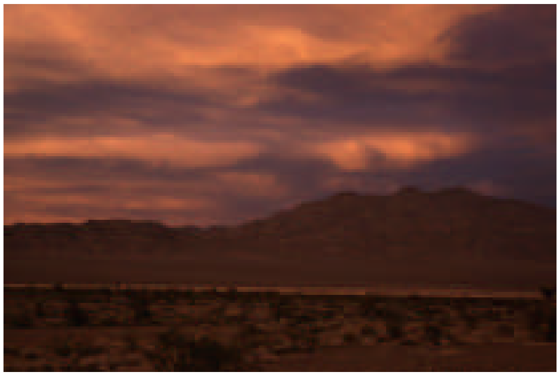

Abstracts appear as they were received from the authors.
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THE PACIFIC DECADAL OSCILLATION AND FLOOD FREQUENCIES IN THE UNITED STATES

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Interdecadal variations of climate over the North Pacific Ocean have been categorized by the first principle component of monthly sea-surface temperatures (SSTs) there, an index called the Pacific Decadal Oscillation (PDO). As during El Niños, when PDO is in its positive phase, the central North Pacific is cool and the waters along the west coast of North America are warm; negative PDOs indicate the opposite temperature patterns. The PDO tracks climate variations that in part are distinct from, and complementary to, the tropical climate variations of El Niqo-Southern Oscillation (ENSO). Together, PDO and ENSO make significant contributions to year-to-year streamflow variability in North America. In order to identify possible PDO influences on the occurrence of floods, the magnitudes of floods with 5- to 50-year return intervals have been analyzed in daily streamflow series from over 1100 streamgages in the United States. At 34% of the gages, estimated magnitudes of 5- to 50-year floods, calculated from annual maximum daily floods in years during which a 5-yr averaged PDO index is positive, are different (at 99% confidence level) from the corresponding flood magnitudes during years in which the averaged PDO index is negative. When the PDO is in its positive phase, e.g., 20-year floods in northwestern rivers average +18% larger and 20-year floods in the south-western rivers are -34% smaller than when PDO is negative. November-March floods in the northwest coastal rivers and through the interior southwest reflect PDO status; April-October floods in the interior northwest reflect the PDO. In order to use such statistics for prediction of flood probabilities, and given the short memory of SSTs by atmospheric circulations and fluxes, analyses were repeated with a version of the PDO index estimated from immediately antecedent SST variations. Flood frequencies are almost as strongly conditioned by this real-time estimate of the decadal PDO variations as by retrospective PDO regimes, encouraging new approaches to long-lead forecasts of flood-frequency variations throughout the country.

Predicting the Effects of Dry Climate on Landscape Development in the Mojave Desert and Southern Colorado Plateau, with Implications for Resource Management

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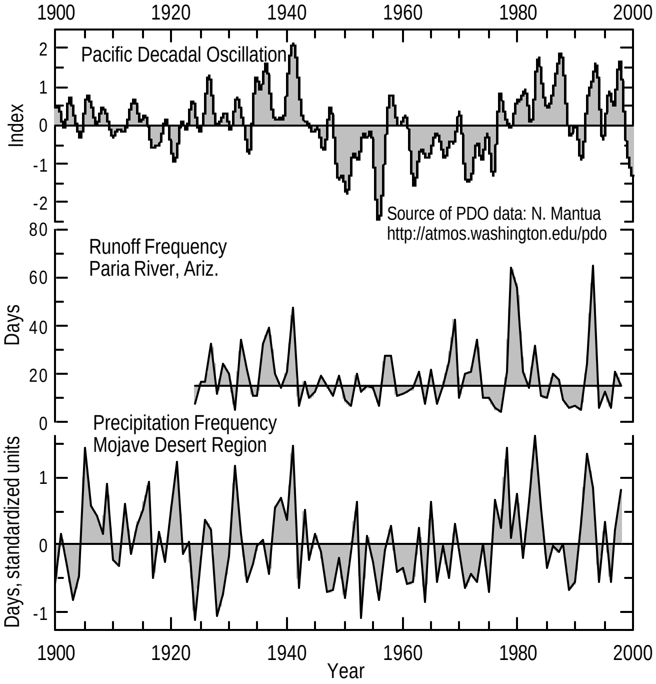
Predicting the effects of climate on landscape development is no less difficult than predicting climate itself. Nevertheless, one can make several broad generalizations by assuming future climate will have about the same effect on alluvial processes as in the recent past. The historic (post-1900) precipitation patterns of the Mojave Desert and southern Colorado Plateau are roughly similar. Precipitation in both regions is influenced moderately by global-climate fluctuations of sea-surface temperature (SST) and atmospheric pressure operating on two time scales; specifically the interannual variations of El Niño and La Niña as expressed by the Southern Oscillation Index and the long-term variations of the Pacific Decadal Oscillation (PDO). For example, during 50 percent of the Los Niños cool-season precipitation was above normal while in 70 percent of them warm-season rainfall was below normal. Conversely, during 80 percent of the Las Niñas cool-season precipitation was below normal, but 50 percent had above normal warm-season rainfall. The PDO (an index of the relative SST of the Northern Pacific Ocean) influences precipitation over time scales of 2–3 decades. The recent cool phase (i.e., cool off the west coast of the Northern Hemisphere) of the PDO from the 1940s–1977 reduced precipitation in the desert and runoff on the plateau, whereas, the recent warm phase from 1978–1998 produced unusually wet conditions in the desert and frequent runoff on the plateau for most of the period.



Source of PDO data: N. Mantua
http://atmos.washington.edu/pdo

Top—smoothed monthly indices. *Middle*—frequency of daily runoff ≥ 95th percentile by year. *Bottom*—average annual frequency of daily precipitation ≥ 90th percentile at each of 52 weather stations.

These long-term changes in precipitation patterns affected hillslope runoff in the central Mojave Desert and alluvial processes in high-order channels of both regions. Although the interpretation is evolving because the data are incomplete, the frequency of overland flow during the cool-phase PDO was low in 50 percent of the studied basins ranging from 0.1 to 10 km^2. Alluvial channels on the southern Colorado Plateau as well as the Amargosa River, Kingston, Death Valley, and Watson washes in the Mojave Desert developed floodplains and aggraded their channels. In the southern Colorado Plateau, alluviation was related to a reduction in the frequency of large floods, a situation enhancing sediment storage in high-order channels. Large, destructive floods were rare in both regions at this time probably because the frequency of high-intensity precipitation was suppressed. In contrast, during the present warm phase of the PDO, high-intensity rainfall was relatively frequent, particularly during the unusually strong and persistent Los Niños that were characteristic of the period. Several relatively large floods in the early 1980s and 1990s eroded the channels and floodplains, producing a terrace in the southern Colorado Plateau streams and scoured floodplain-like features in the desert washes.

If the PDO shifts to a cool phase similar to the 1940s to 1977, as many climatologists infer, stream channels and hillslopes will likely adjust to the new precipitation regimen. The frequency of high-intensity precipitation may be reduced, even during active ENSO (El Niño Southern Oscillation) seasons. Alluvial channels are expected to recover or heal from the floods of 1980s–1990s, as large floods will be uncommon. Floods will still occur, but they should enhance sediment storage on developing floodplains. Riparian vegetation may flourish in this flood regimen where groundwater levels do not drop substantially. Sediment yield, moreover, is likely to decrease because of infrequent hillslope runoff and sediment storage in high-order alluvial channels.

Finally, land managers should consider the potential influence of relatively dryer and warmer climate when planning restoration projects and monitoring biological components of the ecosystem. Restoration projects, investigations of landscape recovery, and studies of floral and faunal population dynamics undertaken in the previous 20 years were done when conditions were unusually favorable. In the near future, persistent dry conditions will stress the flora and fauna of both regions, decrease surface runoff and replenishment of shallow aquifers, and increase recovery times from human disturbances. From the perspective of land management, the differences between the two climates are that in the dry one recovery times will be longer and the ecosystem will be more sensitive to disturbance.

[1] Global Change Climate-History Program–Southwest Project–Climate and Fluvial Processes and Mojave Desert Ecosystem Science Project

Interpreting Climate from Rio Puerco Arroyo Sediments: Cautions about Predictive Models

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Sediment supply may respond to climate variations, particularly in a monsoon-dominated, semi-arid environment. Monitoring of sediment movement will be of increasing importance in many southwestern areas due to increased infrastructure. Can we confidently predict the response of specific geomorphic elements such as uplands, hillslopes, valley floors and arroyos to changing climate? Can we define background rates of sediment flux in various landscapes that provide datums for assessing change? Can we determine the sources of sediments that feed arroyo cut-and fill cycles?

The Rio Puerco, NM has been a site of geomorphic investigation for much of the 20th century. Recent study of erosion using instrumental, cosmogenic isotope and geomorphic techniques provides new data for comparing short and long-term rates. Studies of arroyo stratigraphy provide evidence for periodic rapid rates of sediment aggradation and excavation that can be compared with climate records. We do not have a comprehensive understanding of the response of uplands, slopes and arroyos to climate, but we can assess the relations of short-term processes to long-term steady-state erosion.

The Rio Puerco is, per unit area, a world-class sediment conveyor. Over the period of instrumental measurement of discharge and sediment load, the Puerco exhibits a decreasing yield, interpreted as increasing storage in the arroyo alluvium. Recent research by Peter Molnar (Colorado State University), shows that intrinsic factors, such as increased riparian vegetation, rather than decreases in rainfall or extreme events are the most likely explanations for changes in sediment conveyance.

In addition to sediment load and yield data for the total basin, we have gathered data from smaller basins and areas of topographic inversion. We have instrumented small basins on sedimentary and volcanic substrates, measured cosmogenic ^{10}Be erosion rates, and calculated surface lowering rates relative to stable volcanic and gravel pediments. Recent erosion rates on interbedded sandstone and shale substrates are identical to long-term rates measured by isotopic and geomorphic methods. The interpretation of that result is problematic. At face value, we can argue that sediment production and transport through the various geomorphic reservoirs between the uplands and arroyo mouths is in steady-state over long (e.g. > 1000 year) time scales. There are, however, arguments against such an interpretation.

First is the observational and stratigraphic evidence for repeated filling and cutting cycles within arroyos. If sediment supply is constant, why do arroyos exhibit cyclical behavior? As summarized by Cooke and Reeves, climate and landcover, especially as affected by grazing, have been the dominant explanations. In the Rio Puerco, however, we cannot match arroyo cycles to wet/dry cycles using data generated by Grissino-Mayer from tree-rings. Cultural evidence analyzed by Curt Larsen does suggest that the penultimate arroyo incision around 1500 A.D. was related to drought, but other severe droughts in the tree-ring record are not identified as periods of arroyo incision.

Second, the instumental record from a well-managed, grassland basin the Puerco basin does show that sediment yield can decrease with improving landcover. We can hypothesize that periods of increased annual rainfall and grass-cover prior to intense grazing in the late 1800's were also periods of reduced upland erosion and increased sediment storage. It's possible that the methods we've employed miss the 100 to 1000 year timescale. If so, sediment delivery to the arroyos is cyclical. In a basin the size and geologic complexity of the Puerco it's unlikely that the cycles of sediment storage and release would be everywhere in phase. Thus the small basin data reinforce the evidence presented by Molnar, and previously argued by Schumm, that intrinsic processes are the dominant control on sediment storage in and release from arroyos.

The sediment data from a variety of studies in the Puerco illustrate, therefore, that a simple climatic interpretation of arroyo processes is not possible. The state of the arroyo system (hydraulics and vegetation) may be critical to determining how arroyos respond to climate change, and whether incision or aggradation ensues. We are faced, therefore, with the problem of what type of predictive model might be available. That should be an important topic for this meeting. Our results strongly emphasize the need and opportunity for continued erosion studies combined with monitoring of landcover changes. Substituting space for time, we may be able to design a regionally distributed set of field studies that elaborate how arroyos operate over the 100 to 1000 year timescale.

Relations between Ground-water, Surface-water, Tree-Ring, and Precipitation Variations in the southwestern United States

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Hydrologists studying ground water have often neglected climate-related variations of inflow to and outflow from aquifers. Instead, long-term average recharge rates have been used in the analyses of regional flow systems. In many aquifers, estimates of climate variations can provide useful estimates and predictions of large-scale ground-water variations. Overall, however, the size of climatic responses in any given ground-water/surface-water system can be difficult to specify prior to analyses. The response depends on how closely the ground-water and surface-water systems are coupled, on which system dominates the year-to-year hydrologic variations in a basin, and on the time scales and avenues by which the climate forcings enter the particular hydrologic systems. Given all these uncertainties, responses of different aquifers in different parts of the southwest to climate variations on a variety of time scales need to be quantified, along with concurrent streamflow and precipitation variations, if methods for estimating recharge and understanding ground-water/surface-water relations are to be developed that include realistic climate influences. Analyses of precipitation variability in the southwest show the presence of important and coherent variations with time scales of 20, 6 to 8, 4 to 5, and 2 to 3 years. The corresponding analyses of hydrologic records show that ground-water and surface-water responses to these precipitation variations differ depending on location within the southwest and with hydrologic setting within any one basin. Analyses of dendrochronolgy time series from tree-ring indices will be used to supplement our statistical assessment of decadal and longer climate cycles. It is anticipate that the warmer and drier periods lasting for 20 years or more could have an adverse effect on the ground-water and surface-water resources of the southwestern United States. This could be manifested by reduced recharge as ground-water inflow and increased ground-water discharge as pumpage.

Potential effects of climate change on vegetation in the San Pedro River watershed, southeastern Arizona.

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Climate-driven changes in vegetation distribution and abundance were predicted by a climate-correlative logistic regression model for the San Pedro River watershed in southeastern Arizona. Present-day climate surfaces were interpolated at high spatial resolution using geostatistical methods and included average annual temperature, and warm season, cool season, and total annual precipitation. Existing distributions and abundance of 10 plant species, mapped with high resolution airborne videography, were correlated with climate in a spatially explicit model applicable at the watershed scale. Model climate parameters were manipulated through GIS analysis to simulate 1 and 2 °C temperature increases and 10% increase or decrease in seasonal precipitation. Resulting vegetation maps showed that a temperature rise would be generally beneficial for Sonoran desert species palo verde (*Cercidium microphyllum*), creosotebush (*Larrea tridentata*), and saguaro (*Carnegiea gigantea*), but would be detrimental for other studied species such as encinal oaks (*Quercus spp*.). Changes in precipitation could potentially offset or exacerbate temperature-driven effects on distribution and abundance in some cases. The Chihuahuan desert species tarbush (*Flourensia cernua*) appeared particularly sensitive to changes in the summer:winter precipitation ratio in this geographical region. All studied species appeared strongly affected by even modest changes in temperature or precipitation regime.

Potential Consequences of Climate Change on the Nature and Processes of Flooding on Alluvial Fans in Southern Arizona

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Introduction

Climate change could influence the timing, magnitude, and processes of flash flooding on desert piedmonts (including alluvial fans) and is therefore important for several reasons. Desert piedmonts are huge in combined area, roughly half the Basin and Range province of the western US and northern Mexico, for example. Flash flooding is the paramount geomorphic process of construction and maintenance of many piedmont areas. More and more people live and work on these desert piedmonts and flash floods pose a significant hazard to life and property. Unfortunately there has been a lack of adequate data and theory for understanding flooding through complex distributary channel networks. This explains why flood hazard assessment methods for alluvial fans have been so controversial and litigious, and any consequence of climate change would only exacerbate the problem.

In order to speculate about the potential impact of a change to a warmer and drier climate on the processes and hazards in this setting, we first summarize our understanding of the nature of channels and fluvial processes for hydraulically-steep ephemeral stream networks on alluvial piedmonts in Arizona. That understanding is based on our various studies (including work with Kyle House, J. Dungan Smith, and Jon Fuller). One of our most fruitful methods has been the reconstruction of the spatial distribution and depths of flow for two recent, extreme (100+ year recurrence) piedmont floods: the 1988 flood on Wild Burro Wash fan near Tucson, and the 1997 flood on Tiger Wash fan west of Phoenix. In addition to inundation mapping, we have reconstructed the flow hydraulics of select reaches, evaluated bed scour, and searched for evidence of channel change and new channel formation both in the field and by using time-series aerial photographs.

Nature and Processes of Flooding on Alluvial Fans

Washes on active alluvial fans branch in the downstream direction, but they locally recombine so that the networks are more complicated than an inverted tree. Flow of any kind is unusual, and bankfull events recur over decades to centuries. During extreme floods all channels in the network are involved and flow in overbank areas is extensive, but the entire fan is not inundated. Flow depths and velocities generally decrease in the down-fan direction, but large channels, with deep and swift flow, can occur at any position on a fan. There are relatively few primary threads of flow. Only occasionally does an extreme flood create new channels and/or abandon old ones.

The characteristic channel form in this setting is the repetitive alternation of narrow and wide reaches, where flow is deep in the narrow reaches and shallow in the wide reaches. The gradient of the bed is steepest entering into narrow reaches and least-steep leaving them. Thus, flow converges, deepens and accelerates as it enters a narrow reach. As the bed gradient diminishes the flow widens, shallows, and decelerates as it enters a wide reach. Channels branch only at wide reaches. We believe that repetitive spatial alternation of supercritical and subcritical flow is responsible for the channel-geometry pattern. This theory has withstood several tests involving flow hydraulics and sediment transport calculations and simulation of the resulting distributary network.

The expansion/contraction channel-form is in equilibrium with bankfull discharge, and thus rare, extreme flows. This statement is based on the same logic used by our predecessors who argued equilibrium for perennial meandering streams. First, there are downstream hydraulic-geometry scaling relations among bankfull discharge and channel size; and scaling relations among shape factors such as wide-width, narrow-width, and wavelength. Each site we have studied exhibits these scaling relations. Second, bankfull flows act to construct and maintain the expansion/contraction channels, and the network in general, that was present prior to the flood. The Wild Burro flood modified all channels, but none by very much and no new channels were formed. The Tiger Wash flood created two new major channels but did not destroy the preexisting channels, so the essential character of the downstream branching network was unchanged.

Potential Consequences of Climate Change on Alluvial Fan Flooding

The influence of vegetation on channel and flood-plain maintenance is critical to evaluating the potential influence of climate change. Plants play a less obvious role in channel narrowing in this setting than they do in less arid settings. Where groundwater is shallow or where base flow persists for weeks or months, ephemeral streams tend to change width fairly rapidly through time. They widen during large floods and afterward plants become established on the bed. The plants promote sediment deposition and thus drive channel narrowing during subsequent moderate floods. If similar processes occur on Arizona alluvial fans, the rate of channel-narrowing must be far slower. Channels large enough to convey extreme, rare floods persist in the landscape for many decades without changing substantially. Therefore climate change causing decrease in vegetation should not change the nature of processes operating within channels.

Vegetation in flood-plain or overbank areas imparts drag on overbank flow and promotes flood plain stability. Therefore a change in flood-plain vegetation could influence the frequency of new channel formation and the spatial distribution (channel density) of flow within the network. Upland plants also increase infiltration and decrease runoff velocities to some degree. We speculate that higher temperatures per se, would only marginally influence Sonoran Desert plants near the northern limit of their distribution. Colder climate, on the other hand, could have a significant impact because many plants (like cacti and ironwood trees) are sensitive to prolonged freezing temperatures. Moisture availability is important; thus drier climate could influence plants, particularly if periods of no rain were lengthened.

In conclusion, we speculate that a change to a “drier and warmer” climate in southern Arizona would not change the processes in operation, or the geometry of channels and downstream-branching networks, on alluvial fans. Increases in the magnitude or frequency of hazardous flooding, and the rates of new channel formation could occur if plant cover were reduced, and if changes in atmospheric circulation patterns were to accompany this climate change. If there were an increase in the frequency of tropical storm incursions into the western US, for example, the frequency (but not the nature) of flash flooding on fans with large drainage areas would increase, as would groundwater recharge.

Interaction of climatic, anthropogenic, and other factors in late Holocene fluvial change in McElmo and Chaco canyons, Four Corners region

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Two late Holocene fluvial sequences in the Four Corners region of the Colorado Plateau show more-or-less mechanical factors with which climate change has to interact to produce change in the fluvial system. Both sequences are dated by numerous Anasazi remains, commonly to within 50 years or less, between about A.D. 500 and 1300 (1450 to 650 BP). Studied stretches of the west-flowing drainages are ~8 km long. Sandy late Holocene sequences 4 to 8 m thick are well exposed in the walls of modern arroyos formed in the 1800s. Dating and other archaeologic advice was from Tom Windes and Gwinn Vivian at Chaco Canyon and Wayne Howell and the Crow Canyon Center in McElmo Canyon.

The McElmo Canyon deposits in southwest Colorado can be taken as an end member showing complex response (in the sense of Schumm). Two aggradational pulses separated by about 200 years migrated 7 km upstream, each requiring about 200 years to do so, thus bracketing a diachronous entrenchment episode from about A.D. 750 to 1150. The driving factors are unclear, but complex response is generally thought to be driven by base-level change.

At Chaco Canyon in northwest New Mexico, a valley floor perched apparently behind an eolian dune was entrenched to meet the rest of the system at grade when the eolian dam was breached (as it is currently). Arroyo cutting was much faster than at McElmo Canyon, within the resolution of the age data. Cutting of the "post-Bonito channel" of Bryan occurred between about A.D. 950 and 1025, filling about A.D. 1025 to 1090. This is consistent with the more mechanical, on-off nature of base-level control.

Base-level change is apparently the one common thread in these two otherwise different sequences. In Chaco Canyon a balance between fluvial and eolian activity influences base level, and this clearly is one measure of paleoclimate. Other factors, though, were probably controlling base level also in both sequences. Many of these are anthropogenic, they include land-use change and consequent change in rate of erosion, agriculture-related sediment storage, manipulation of drainage pattern , and temporary extermination of beaver. The net effect of anthropogenic activity is unclear as some components may work in opposite directions, but entrenchment in each case approximately coincides with the earliest intensive use by man (as it did in the 1800s). Stream capture and meander-loop cutoffs are some non-human factors, probably more important at McElmo Canyon.

These factors, both anthropogenic and natural, suggest some of the tools that actually change fluvial systems. Climate change adjusts fluvial systems by using the tools, but so can man, and so can other natural processes.

In view of the mix of climate-driven and anthropogenic effects, prediction involves guessing what man will do next. The effect of climate on beaver and vegetation is more predictable but man influences their importance. Perhaps the most important climatic ingredient is the relative importance of eolian and fluvial activity. Where eolian processes are dominant, some drainages may become segmented by dunes.

Climate behavior: How relevant is the past to the future?

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The goal of this discussion is to dredge up for closer examination some of the hidden assumptions we make about climate. Information about past climate has direct and indirect applications in the decision-making environment, including that of water management and planning. Common practice is to acquire data about climate and related elements (such as streamflow), for whatever period is available, and then make the tacit assumption that the characteristics of interest for this past interval will continue to apply over the time scale which the decision is attempting to address. How comfortable should we be with the results of this process? Examples from flood frequency analysis will be used, and perhaps others.

The Morphological Representation of Channel-Forming Flows in Arroyos – a Report on Work-in-Progress

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This presentation will outline the work of the author currently being undertaken to fulfil the requirements of a doctorate degree. The project aims to relate the morphology of contemporary arroyos to the discharge variability and antecedent sequence of events within the system. It is generally considered that channel-forming discharge theories related to a particular discharge have limited applicability in arroyos. Completion of the project will provide detailed data and explanation as a contribution to this debate.

The project requires arroyos which have at least fifty years' discharge data and which have been monitored for a similar length of time in order to determine the effects of different magnitudes and frequencies of flow. It was determined that, of the arroyos in the southwestern USA, there were only three systems which met these categories: the San Simon and Santa Cruz Rivers, Arizona and Rio Puerco, New Mexico.

To understand the background of the study systems in their catchment context, a catchment baseline survey and fluvial audit have been completed. The baseline surveys permit a qualitative framework of catchment processes to be derived. It has been determined that the three study sites differ considerably in morphology and geomorphology, although all three have some similarities. The reconnaissance enabled reaches within the system representative of the variety in arroyo morphology to be determined. These representative reaches have been accurately surveyed in order to determine the contemporary channel morphology and variability within and between these reaches. Along each chosen reach, several cross-sections have been surveyed parallel to the active channel. The cross-sections will be used, in conjunction with detailed photographic records, to determine the geomorphological units within the arroyo, in particular which features have been formed by fluvial processes. This information will be used in conjunction with discharge data to determine the importance of fluvial processes.

Flow and sediment discharge data has been collated from USGS and BLM gauging stations. The arroyos in Arizona only have daily average discharge data and little sediment concentration data. However, it was possible to calculate 15 minute data for one gauge along the Rio Puerco by digitizing the original gauge height strip charts. The Rio Puerco also has comprehensive instantaneous sediment concentration data. This data will be used to calculate a flow duration curve and sediment rating curve for each system. These will be combined to produce a sediment load histogram, the peak of which indicates the effective discharge.

The flow data will also give an indication of the change in flow dynamics over the period of record. The discharge variability and antecedent sequence of events which have combined to create the contemporary channel morphology will be examined. All three study sites have been closely monitored since the systems began evolving in the late 1800s. Aerial photographs, ground level photographs and former channel cross-sections have been collected. The contemporary channel morphology will be compared with past channel morphologies and the difference related to the pattern of flows which occurred in the interim. This will determine the behaviour of the system in response to the hydrological regime within a historical context.

Having analysed the hydrological regime of the arroyo system, including determining whether an effective discharge can be calculated, the contemporary channel morphology of the arroyo will be analysed in the context of these findings. The morphological forms and features will be related to the level of the effective discharge to examine whether this discharge level is truly a channel-forming flow. Thus it will be determined whether a single channel-forming discharge controls the morphology of arroyo systems and, therefore, whether channel-forming discharge theories are applicable.

This project will, when completed, further the understanding of arroyo behaviour in response to a changing hydrological regime. As yet, however, some data collection and much data analysis is still to be completed. The purpose of this presentation is, therefore, to inform attendees of the proposed research concept and to invite comments.

USE OF REMOTE SENSING TO DETECT CHANGE AND LANDSCAPE CHARACTERIZATION

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Wind-induced emission of dust from the land surface is a process of degradation that: depletes fine-grained minerals needed for optimum vegetation growth, creates potentially hazardous air quality for humans on a local and regional scale, and affects climate on a regional and world-wide scale. Future climates may lead to further aridification of southwestern deserts that in turn would reduce protective vegetation and thereby enhance dust emissions. Currently, it is not well understood how enhanced dust emission will affect climate.

We are using remotely sensed satellite, airborne, and ground-based images to detect wind erosion and vegetation change as well as their relations to climate in the southwestern United States. The image data are particularly useful for monitoring the regional ecosystem that requires the capability to map and characterize surface and landscape features. Vegetation cover, changes in vegetation cover and density, and surface soil properties are critical parameters to determine wind erosion vulnerability and to evaluate a variety of related ecosystem conditions (such as plant and animal species diversity and populations). Ultimately our goal is to provide a database relating measurements of 1) ground-based meteorological parameters, 2) digital maps generated from remotely sensed images showing sand and dust sources, 3) digital vegetation change image maps generated from the remotely sensed satellite images, 4) digital maps of surface particle size for geomorphic units in the Mojave Desert vulnerable to wind erosion, and 5) surface armored image maps. These results will provide elements essential to understand how desert surfaces will respond to future climate using regional-scale climate models.

Response of semi-arid vegetation to predicted climate change: A project update

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Global change may make obsolete the conventional knowledge of land managers on vegetation regeneration and succession. In order to manage vegetation, land managers must make determinations of potential future conditions. This requires prediction of the expected trajectory of species response to climate change and secondary stressors that can accompany changes in the environment.

This project, part of the Biological Resources Division Global Change Program, is investigating a series of questions related to understanding the response of species to climate change over a broad region. Specifically, the research asks:
1) How will plant species distribution potentially shift during projected climate change?
2) What geographic areas are vulnerable to shifts in species composition during projected climate change?
3) What is an effective change detection procedure for resource managers to monitor these projected climate changes?

We are characterizing the current niche parameters of a select number of species on an elevation gradient including the eastern Mojave and western Arizona. Classification tree models, also known as decision tree models, are being used to describe species distribution space at a resolution of 1 km. using a set of topographic, substrate and current climate variables mapped over the entire region as the predictors. Species redistribution under two times CO2 conditions will be predicted by substituting predicted climatic variables into the niche models.

The potential of a landscape to support species is expected to change under current climate change predictions. One factor affecting the probability of a landscape being populated with new species is the ability of a species to migrate and colonize the new environment. The influence of dispersal and migraton on potential redistributon of species will be examined in the GIS environment using project developed 'migration' metrics.

Landscapes which experience dieoff of current species and experience delay in colonization by desireable species due to migration lags may be vulnerable to invasion by undesireable species, such as invasive exotic plants. Potentially vulnerable landscapes will be identified.

Predicting Changes using Multi-date Satellite Imagery: San Pedro River Case Study

(presented by David Goodrich, A.R.S.)

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Vegetation change in the American West has been a subject of concern throughout the twentieth century. Although many of the changes have been recorded qualitatively through the use of comparative photography and historical reports, little quantitative information has been available on the regional or watershed scale. Additionally, little research effort has been dedicated to improving human understanding regarding changing conditions and trend relative to planning and management of common resources at regional landscape scales. During the past two decades, important advances in the integration of remote imagery, computer processing, and spatial analysis technologies have been used to better understand the distribution of natural communities and ecosystems, and the ecological processes that affect these patterns. These technologies provide the basis for developing landscape measurements that can be integrated within hydrologic and nonequilibrium models to determine long-term change and make predictive inferences about the future.

This case study employs a system land cover maps generated from a multi-date satellite imagery database which incorporates Landsat Multi-Spectral Scanner (MSS) imagery from the early 1970s, mid 1980s, and early 1990s and Landsat Thematic Mapper (TM) imagery from 1997. It has been tested over the Upper San Pedro Watershed (U.S./Mexico) where results indicate that extensive, highly connected grassland and desertscrub areas are the most vulnerable ecosystems to fragmentation and actual loss due to encroachment of xerophytic mesquite woodland and urbanization. In the study period, grasslands and desertscrub not only decreased in extent but also became more fragmented. That is, the number of grassland and desertscrub patches increased and their average patch sizes decreased. In stark contrast, the mesquite woodland patches increased in size, number, and connectivity. These changes have important impact for the hydrology of the region, since the energy and water balance characteristics for these cover types are significantly different. This study has been used to determine ecosystem vulnerabilities through the use of change detection and indicator development, especially in regard to traditional degradation processes that have occurred throughout the western rangelands involving changes of vegetative cover and acceleration of water and wind erosion.

Predicted Changes In Mojave Fire Frequency Related to Invasive Annual Grasses

T. C. Esque, L. A. DeFalco, P. A. Medica, M. L. Brooks and R. H. Webb

Predictions of climate change for the next 20 years suggest that conditions could become increasingly hot and dry in the Mojave Desert. If this prediction becomes reality, the frequency and size of fires may be diminished due to reduced vegetative cover and biomass, especially invasive annual grasses. Trends in vegetation production over the past 40 years show that production of annual plants is positively correlated with winter precipitation. Production increases are accentuated by invasive annual grasses, which are more prolific than many natives but do not have the seed bank persistence of native annual species. The most pervasive of the invasive annual grasses in the Mojave Desert is red brome (*Bromus madritensis* formerly *rubens*).

Invasive annual grasses, such as red brome, depend on winter and early spring precipitation to complete their life cycles and thus should be affected by reductions in this precipitation. However, the amount of adaptive plasticity these plants have shown by radiating throughout habitats in the arid western United States provides another precaution about predicting declines in the distribution of the species. We speculate that invasive annual grasses will continue to flourish in high elevation refugia during the most severe droughts, and elevational fluctuations will vary with available soil moisture. This hypothesis is supported by observations of population crashes at low elevations but survival and reproduction of red brome at high elevations during years when regional rainfall totals were well below the long-term average in the Mojave Desert. The current spates of fire introgression into the low-elevation desertscrub and shrub steppe habitats will diminish, but greater frequency of fires at higher elevation should occur where mesic conditions can allow invasive annual grasses to persist. Furthermore, short wet periods during the next 20 years could result in minor incursions back into low elevation habitats, and repeated fire disturbances requiring long recovery times could occur.

Based on a combination of data with a healthy amount of speculation, we expect red brome to respond to the switch to a hotter, drier climate in the following scenarios:

- Red brome is expected to decline across the current range due to poor dormancy mechanisms, low seed bank persistence, and reduced survival of seedlings germination owing to drought. The effects of N deposition, and possibly increased atmospheric CO_2, may offset this decline in local areas due to increased resource availability. Alternatively, red brome may decline briefly, then regain prominence due to genetic variability or plasticity that provides for drought tolerance (i.e. genes coding for dormancy mechanisms may increase in the gene pool). Recovery of red brome populations from drought may occur more slowly than the original colonization due to the development of dormancy mechanisms that reduce overall rates of germination.

- Populations of red brome become reduced in desertscrub and shrub steppe but maintain numerical dominance in mixed conifer and oak woodlands. As a result, red brome may expand into higher-elevation sites. If the climate becomes hotter and drier, then seeds would not necessarily need to withstand colder temperatures, unless the climate fluctuated more radically. We should expect an adjustment of vegetative communities as species shift to track climatic change and we predict that red brome, and other invasive annual grasses are especially suited to respond to such changes.

- All these scenarios generally lead to a decline in the current prominence of invasive annual grasses in desertscrub and shrub steppe.

With the decline in invasive annual grasses in desertscrub and shrub steppe, the amount of standing organic matter that fuels fires will decline. As a result, the frequency and size of fires in desertscrub and shrub steppe habitats should be reduced. Fire may continue at current frequencies in mixed-conifer and oak woodlands. Fire regimes at higher elevations may or may not change if red brome encroaches, because many middle-elevation habitat types are dominated by fire-tolerant for fire-dependent species. However, if the fire-return rate increased from several decades or more to every-other-year, then this trend might change the vegetation communities affected by the encroachment of red brome. Previously disturbed areas, many of which are currently dominated by red brome, could slowly return to desertscrub or shrub steppe with the recovery of native annuals and perennials. Some previous work has suggested that certain vegetation associations of the Mojave Desert – in particular blackbrush (*Coleogyne ramosissima*) assemblages – are not expected to recover owing to increased fire frequency related to increases in invasive annual grasses. Our long-term work in blackbrush assemblages in the northern Mojave Desert suggests that recovery does indeed occur and that non-native grasses may not have the effects postulated from other parts of the Mojave. We expect that all population dynamics would be slowed due to the low winter precipitation, resulting in slower recovery rates of previously disturbed areas. New drought tolerant species could invade these areas, and the potential candidate species are at present unforeseen. In other words, drought could neutralize the current concern that invasive species are initiating a type conversion from desertscrub to annual grassland, but the potential for other invasive species makes prediction of this outcome tenuous at best. Invasive grasses such as red brome are predicted to remain part of the landscape, although their local distributions may shift up and down mountainsides and into the valleys during pluvial periods.

Ecological responses to climate, land-use change, and eolian deposition: New approaches to modeling terrestrial biogeochemistry.

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Terrestrial responses to environmental change are controlled by numerous factors including plant functional types, hydrology, and biogeochemistry. Ecosystem models generally focus on the interaction of nitrogen and water in controlling plant growth and ecosystem carbon exchange. In desert ecosystems, however, many elements including phosphorus and base cations may limit primary productivity. Moreover, hydrologic and biogeochemical cycles are strongly influenced by spatial variations in parent material and patterns of eolian deposition. These controls are not well integrated into prognostic models of ecosystem response to changing climate yet are critical to understanding both current and future patterns of ecological dynamics in arid environments. As part of an NSF funded Integrated Research Challenges project titled "Biological Control of Terrestrial Carbon Fluxes" at the Natural Resource Ecology Laboratory, Colorado State University, we are developing a new terrestrial ecosystem model. This new model includes a vertically structured soil profile, a detailed hydrologic submodel and simulation of multiple isotopes of carbon and nitrogen. This modeling effort also includes the development of land use databases with which to evaluate the past and future impacts of land use on terrestrial processes. In collaboration with the USGS, we are also beginning work to incorporate geologic and eolian controls over ecosystem dynamics. This work will include evaluation of the role of essential and limiting elements in ecological processes, detailed linkages between hydrology and biogeochemistry, and the capability to simulate the direct effects of climate change on vegetation and soil processes, such as temperature and moisture controls over processes. This model will also include representation of the indirect effects of climate change on ecosystems through the incorporation of weathering processes and centennial time scale changes in ecosystems composition, as well as response to both biological invasions and changing biogeochemical and hydrologic regimes.

Eolian Dust in Southwestern Soils: Changes in Nutrient Inputs Related to Climate Change and Land Use

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Studies of eolian dust in soils of the southwestern U.S. broadly address issues of arid-land ecology and biogeochemistry (the sources and timing of nutrient inputs) as well as vulnerability of arid landscapes to climatic variability and land use. We have developed a new combination of methods, primarily using magnetic properties, to detect the presence of wind-blown dust in young arid-land soils. The method is rapid and, combined with chemical analyses, enables us to evaluate the role of such dust in delivering nutrients to landscapes on the scale of ecosystems. These studies serve as a foundation for further work to understand the geologic and ecologic factors that drive vegetation type at both landscape and local levels, including invasive plant species.

Eolian dust in the typically sandy soils of the central Colorado Plateau is responsible for much of the soil fertility of the Canyonlands area ecosystem, and its chemical composition likely influences plant community composition. A change in dust sources over the past several decades is documented by different chemical and mineralogic properties of dust trapped in stable (~50 yrs) surfaces of biologic soil crust compared to those properties of dust in underlying deposits. Some of the recently fallen dust may result from human disturbance of the land surface far from the central Colorado Plateau.

Similar studies of the fine fraction (< 63 µm) in surficial deposits from the central Mojave Desert document eolian inputs to alluvial deposits and to a thin silt veneer on nearby peaks, even though these settings are much more complex in geologic substrate and magnetic mineralogy than those on the Colorado Plateau. The influence of geologic terrains on patterns of eolian input is revealed by consistent differences between magnetic and chemical properties of fines in and near the volcanic Greenwater Valley area of Death Valley compared to those properties of fines in the dominantly metamorphic and plutonic Valjean Valley area, 75 km to the south. Differences in eolian dust composition, mineralogy, and texture in the upper 10 cm of sediment on early Pleistocene to late Holocene alluvial fan surfaces in Valjean Valley reflect changes in source area with time. Holocene surfaces, which receive dust predominately from modern alluvial sediment, are relatively enriched in P and Mn, for example. In contrast, Pleistocene surfaces, which appear to retain a record of repeated deflations of pluvial lake beds on the basis of particle-size and chemical similarities to playa sediments, are relatively enriched in Mg.

Whereas dust deposition can enrich soils, erosion of eolian fines can also remove valuable nutrients. Replenishment of the lost nutrient-rich eolian material would then depend on future dust input. Existing climatic and landscape conditions, however, differ substantially from past conditions of major dust generation and input in southwestern deserts. The future nutrient load in these Southwestern soils thus depends on the balance of nutrients lost and gained, as well as composition of future dust inputs, all of which will be influenced by climatic variability and human activity as they modify southwestern landscapes.

By linking a new wind erosion model with a regional climate model, we plan to address the following questions: How does wind strength vary with natural climate cycles on decadal time scales? To what extent will winds become stronger or weaker under future climate scenarios? How will soil moisture and vegetation changes affect wind erosion in the future? As an example, projections of doubled atmospheric CO_2 (above pre-industrial levels) for the southwestern U.S. suggest a decrease in winter soil moisture, which may enhance wind erosion. The growing population by itself will likely increase regional dust emission. We may eventually be able to predict whether or how patterns of climatic variability and dust emission would affect nutrient delivery to different depositional surfaces from knowledge about the chemistry of dust-emission surfaces combined with understanding of dust transport pathways under future climates.

Monitoring Dust Deposition in the Western U.S.: Rates, Compositions, and Relations to Climate

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In arid environments, there are close links between climatic conditions and eolian erosion and deposition. However, published studies that attempted to link modern weather patterns and consequent changes in soil moisture, sediment supply, and wind erosion with episodes of blowing dust and changes in dust deposition rates (dust flux) have obtained variable results. Some found increases in dust flux after large rainfall events that deliver erodible sediment (e.g. Reheis and Kihl, 1995); others found decreases in dust storms following periods of increased winter moisture and resultant vegetative cover (e.g. MacKinnon et al., 1990). Deciphering the sources of desert dusts is also problematic, and it is likely that sources have changed since the late Pleistocene as climate has varied and vegetation communities have migrated. Furthermore, human sources now produce a significant component of dusts and aerosols, both by disturbance of natural land surfaces and by industrialization. Because the stability and health of many ecosystems depend on the interaction of eolian dust, vegetation, and geomorphic surfaces, a better understanding of the relations of modern dust to sources and weather patterns is needed to predict the response of arid land surfaces and vegetation to future climate change.

We have monitored deposition rates and analyzed dusts from numerous sites in the southwestern U.S. using a variety of collection and analytical techniques. These sites include marble traps in the Mojave and southern Great Basin deserts that have been maintained for over 15 years, as well as some sites established in the past three years in Utah, southern Nevada, and southern California. The latter sites include several types of dust samplers as part of meteorological stations at low elevations (Clim-Met stations) as well as winter snowpack sample sites in high mountain ranges.

In general, average fluxes of <50-_m dust measured in marble traps increase in parallel with mean annual temperature from the southern Great Basin Desert (4-8 g/m^2/yr) southward through the Mojave into the Sonoran Desert (14-19 g/m^2/yr). This overall increase is complicated by patterns of local topography, wind direction, and land use. At any one site, annual dust fluxes during the past 15 years vary by at least a factor of three. In the Mojave and Sonoran deserts, annual dust flux (and thus presumably wind-erosion rate) may be substantially greater in the year following the increased precipitation of an El Niño year, whereas dust flux at sites farther north is less affected by ENSO patterns. A broad regional average of dust flux from high altitude snowpack measurements was about 20 g/m^2/yr following the El Niño, contrasting with about 5 g/m^2/yr in earlier and later years; lower elevation dry deposition plate collectors indicated dust flux about 100 g/m^2/yr following the 1998 El Niño, contrasted with values about 30 and 15 g/m^2/yr at earlier and later times, respectively. “Flash” summer storms that cause large runoff and supply fresh sediment to washes can also increase local dust fluxes. Hence, if increasing aridity in the desert Southwest is accompanied by a larger proportion of intense rainfall events, wind erosion and dust flux may increase more than would be expected from a change to aridity alone. In the future, increased dust may be expected in years following El Niño.

The composition of Southwestern dust plays an important role in soil genesis and plant nutrition. The major-element composition of the dust is approximately the same as that of a mixture of typical major igneous rock types that make up the crust of the earth. We have variable data on carbonate content of dust samples. As estimated from elemental analyses, dusts collected using plate collectors at lower-elevation sites typically have very limited carbonate components, whereas carbonate is typically a substantial fraction of the total dust in high-altitude snowpacks during the winter half of the year. In contrast, carbonate content of dusts from marble traps is related to local sources, such as limestone alluvium, rather than to altitude.

The trace element composition of the dusts is different from that of average crustal rocks. Arsenic, bismuth, antimony, cadmium, copper, lead and zinc are more abundant in dusts collected on dry deposition plates than in average crustal rocks by factors of 3-10. The enrichment factors are much larger for the fine, far-transported dusts in high-altitude snowpack (commonly >10). These data are consistent with results of trace-element analyses of dust samples from marble traps. Part of this enrichment may be natural: trace element enrichments in fine dusts (snowpack) are similar to those seen in dusts in pre-industrial industrial polar ice. But industrial processes, and specific source areas (e.g.: arsenic, antimony, and zinc from Owens Valley) may contribute to part of the trace element elevation of modern dusts in the Southwest. The trace element cesium is also strongly enriched in dusts, because it is an abundant constituent of the layer-silicate minerals (micas and clays) that are preferentially taken up and transported as dusts, because of their grain shapes. These minerals, with their large chemical exchange capacities in soils, are an important component of southwestern ecosystems, and eolian processes have a key role in their accumulation and depletion. In a more arid climate, surficial deposits might be more susceptible to mobilization into air-borne dust by high-energy storm events, leading to both larger amounts of dust and a greater fraction of dust being recycled, hence less enriched in trace elements.

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Development of a Wind-Erosion Model for the Mojave Desert, USA and its Greater Climatic Role.

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Studies of soils, surficial geology, and vegetation are being integrated with monitoring of landscape change, dust events, and meteorology to understand the conditions that promote dust emission in the Soda Lake-Devil's Playground area, Mojave Desert. The results will be used to test a (computational) wind-erosion model that is broadly applicable to arid regions. Our wind-erosion model, which includes sand transport, combines an atmospheric boundary-layer (ABL) model and an aeolian-response model. Erosion is described for conditions when the wind stress from the ABL model exceeds the threshold wind stress from the aeolian-response model. The wind stress from the ABL model depends on the free-stream wind speed above the boundary layer, atmospheric stability, and local topography. The threshold wind stress depends on the size distribution of soil particles less than 1mm in diameter, surface soil moisture, mineralogical and biotic crusts, and cover by lag particles greater than 1mm in diameter and by vegetation.

At three distinctive geomorphic settings, wind profile, air temperature, precipitation, atmospheric stability, soil moisture, and sediment flux are monitored. Remote digital cameras, overlooking each site from a distant mountaintop, are triggered to image the three sites at low and high resolutions when winds exceed about 6 m/s. For sufficiently intense dust storms, geostationary satellite data are used to supplement the camera monitoring. The meteorological data, sand-flux data, and observations of dust emission provide information against which to test the wind-erosion model. Seasonal vegetation surveys are undertaken to assess changes in landscape vulnerability to wind erosion and to calibrate vegetation change detection maps produced from satellite images. These tests began in October 1999 and will run for three or four years.

Our wind erosion model has been derived from the work of a large body of researchers prior to our current efforts to apply and test the model in the Mojave Desert. Recent applications of similar models to simpler environments than ours have shown good comparison between predicted aeolian response and observations of dust emission at the local to the regional scale. Several parameters in all these models, however, remain poorly related to universally measurable soil, vegetative, and atmospheric properties. For example, the sheltering affects of porous vegetation still have an uncertain relationship to plant shape, optical or volume porosity, and surface distribution. Dust-emission rates can vary by a factor of 50 among soils having similar classifications because the clay components have different, poorly understood, binding energies. Binding energies also effect the establishment of wind-resistant surface crusts formed by water and other biological processes. Subsequent destruction of these crusts by wind and still other biological processes remain completely undefined and unconstrained.

A drier and warmer climate can affect the wind erosion rates in several complex ways. While warmer and drier winters yield less water to erode and distribute vulnerable sediments, there is also less water to stabilize the surface with crusts and vegetation. Wind stresses during warmer and drier winters will be no more predictable than present, because they depend on horizontal temperature gradients between adjacent air masses which, in turn, are driven by a complex land-ocean-atmosphere interplay. To what degree seasonal wind directions and intensities will be changed is also uncertain. However, for the same free-stream wind speed above the boundary layer, average wind stress at the surface will increase in a warmer and drier climate, leading to higher mean levels of wind erosion. Warmer summers may not necessarily be drier. Stronger land heating may cause higher moisture fluxes and more vigorous thunderstorms, preceded first by strong local wind erosion and followed second by vigorous fluvial transport of sediments. A warmer summer season with higher atmospheric instability over flat areas may result in more frequent and intense wind-devils and dust devils, where sediment is available. These summer season events may erode, expose, and distribute sediments so as to increase wind-erosion vulnerability during the winter in an otherwise drying climate. Clearly wind erosion models must be integrated with other climate-sensitive, surficial-process models as part of a whole system model before the wind-erosion consequences to a drier and warmer climate can be fully understood.

Definitive parameters and modeling of the saprophytic habitat of *Coccidioides immitis* in Arizona with a spatial fuzzy system

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Coccidioidomycosis is a public health issue of increasing importance to humans in the southwestern U.S. and in parts of Central and South America. It also affects domestic animals and wildlife. It is caused by *Coccidioides immitis,* a dimorphic soil-inhabiting fungus. The saprophytic phase of the fungus is characterized by branching segmented hyphae that form a network of mycelium in the upper (5 - 20 cm) horizons of soils. As the fungus matures arthroconidia (spores), 2 to 5 microns in size, are formed as barrel shaped, rectangular segments of the hyphae that can be easily separated by soil disturbance (natural or anthropogenic) and consequently dispersed by the wind. If airborne arthroconidia are inhaled by an appropriate host primary infection may occur and the parasitic phase of the *C. immitis* lifecycle is initiated.

Soil characteristics that provide the necessary conditions for the growth of *C. immitis* are; 1) soil temperature (controlled by the amount of sunlight, vegetation cover, soil color, rainfall, cloud cover, elevation, slope, and sun aspect); 2) soil textures that provide adequate pore space for moisture, oxygen, and growth; 3) soils containing some organic material content for the supply of carbon and nitrogen; and 4) soils with a capacity to hold some moisture in the upper (30 cm) parts of the profile. In Arizona, the combination of these essential factors is mostly present in soil families mapped as hyperthermic arid, thermic arid, and thermic semiarid soils. All of the known *C. immitis* growth sites in Arizona are located in these three families. These soils cover approximately 16,443,000 hectares in Arizona and are generally distributed throughout the southern third, along the western border, and along the bottoms of the deeper canyons of the state. The mean annual soil temperatures of these soils ranges from 15^0 C to over 22^0 C and they receive annual precipitation from less than 250 mm to 410 mm.

Habitat modeling of the saprophytic phase of the *C. immitis* life cycle is difficult due to the limited number of known growth sites. This confounds the establishment of statistical relationships of the physical, chemical, and biological habitat parameters. Therefore, habitat modeling is being accomplished using analysis of the physical properties of known *C. immitis* sites and a spatial fuzzy system. The fuzzy system is capable of translating structured knowledge into a flexible numerical framework and processing it with a series of if-then rules called fuzzy associative memory rules. In effect, the fuzzy system reduces the dimensionality of the system to a manageable set of fuzzy variables.

The fuzzy system was applied to each 30m spatial cell over the study area, Organ Pipe Cactus National Monument, Arizona. The resulting product is a map depicting each cell's favorableness for hosting *C. immitis* based on a scale of 0 to 1, which we define as its fuzzy habitat suitability index. The fuzzy system allows modelers to change and update relationships between the variables as more is learned about *C. immitis* habitat. It also allows dynamic representation of climate related variables and can be used to predict changes in habitat with changing climate.

Changes in temperature and precipitation over time will directly influence soil characteristics critical to the growth and propagation of C. *immitis*. Based upon our present knowledge of *C. immitis* habitat, climate change models that predict increased moisture in current endemic areas may result in decreased habitat for *C. immitis.*

Historic climate variability and vegetation dynamics in the southwestern U.S.: Empirical needs for predicting future vegetation change

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Deterministic and statistically-based biogeographic models, coupled with Atmospheric General Circulation Models, are being used to predict large-scale vegetation responses to future climate change. One deterministic model relates site water balance to the distribution of physiognomic types or biomes by way of the difference between potential and actual transpiration over an annual cycle; the direct effects of CO_2 are simulated through changes in stomatal conductance. By contrast, statistical biogeographic models envision plant distributions as stochastic, spatial realizations of response surfaces, decision trees, and bioclimatic envelopes- functions that describe the way in which each species' expected distribution and abundance depend on the combined effects of several environmental variables. Both the deterministic and statistical biogeographic models yield impressive maps contrasting modern (Map A) with potential (Map B) vegetation under doubled-CO_2 climatic scenarios, assuming equilibrium conditions.

What these biogeographic models don't yield is a dynamic view of the slow and complex ecological processes involved in getting from Map A to Map B, a progression that will surely take more than a millennium to complete. These processes include migration, succession, biotic interactions, and hydrological and biogeochemical processes that vary with the life histories of the organisms, the initial conditions and intrinsic rates of change. For most organisms and ecosystems, there are currently few empirical data to support dynamic biogeographic models that can predict transitional stages between Map A and Map B for any point in time and space. These are the kinds of predictions that might prove most useful for anticipating consequences of climate change for ecosystem and resource management on decadal to century scales. I will present a few examples of how historical, large-scale analyses of migration and demography can serve empirical needs for anticipating ongoing and future vegetation change in the western U.S.

Ongoing, natural plant migrations are more widespread than currently recognized by ecologists and land managers; the early to late stages of such ongoing migrations can be studied to answer key questions about migrational dynamics. For example, if vegetation is inherently stable, are there thresholds that jumpstart extirpation of incumbent species and immigration of new taxa? What are the empirical rates of population growth and expansion? Does history of migration (time of arrival) determine the assemblage of associated herbivores, pathogens, and soil fauna? Do individuals and populations grow faster in peripheral (founder) than core populations because of the migrational lag in the associated herbivores, seed predators, and pathogens? In migration, how do competition and climate figure in the replacement of incumbent taxa? How does position on the landscape determine the pathways of invasion? How does migration affect disturbance regime, community composition, structure and diversity, nutrient distribution and cycling, and the flows of energy and water within ecosystems? What are the climatic spaces or topographic wedges that can accommodate ongoing and future migration? How will current and future land use modulate migration? What are the tradeoffs between increasing habitat fragmentation yet unlimited dispersal opportunities, courtesy of our road systems? These issues will be discussed in the context of well-documented late Holocene and ongoing migration of Colorado pinyon (*Pinus edulis*), ponderosa pine (*Pinus ponderosa*), and Utah juniper (*Juniperus osteosperma*) in the central Rockies.

The second part of my presentation will focus on regional synchrony, or spatial autocorrelation, of disturbance and demographic phenomena. Many biotic and abiotic factors exhibit synchrony over large geographic areas. Understanding regional synchrony is essential to evaluate theory about what regulates local and regional populations, and for predicting thresholds and other nonlinear processes associated with vegetation change. For example, broadscale tree mortality during catastrophic drought and other disturbances (fire, insect and pathogen outbreaks) resets demographic clocks and opens niches for new recruitment across the region. Succession of the dead can involve individuals of the same species, other local species that increase at least temporarily, or extralocal species concurrently undergoing migration.

Studies of synchrony require extensive regional networks of long-term data, multiyear for birds and mammals to multicentury for conifers. Tree-ring data can be used to examine regional synchrony, not only in tree growth, but also in vegetation disturbance and demography. Synchrony is embodied best in the ability to cross-date a Douglas fir from southern Arizona with a ponderosa pine from northern New Mexico. Tree growth, fire occurrence, insect outbreaks, and demography are entrained across the southwestern U.S. by cool season (frontal) precipitation, which varies little in space but greatly in time, usually in lockstep with large-scale indices of climate such as SOI, PNA, PDO, and CTI. The cause of regional synchrony is evident not in comparing time series from one site to another, but in correlating spatially-aggregated histories of disturbance or demography to independent, dendroclimatic reconstructions. Understanding the scales and causes of regional synchrony, as well as knowing the disturbance and demographic histories of regional vegetation, are essential for forecasting future vegetation change. I will use disturbance and demographic histories of dominant trees in the southwestern U.S. to illustrate interannual and interdecadal climatic effects on regional vegetation.

In the final analysis, I will present evidence that the growing season has lengthened in recent decades. The coincidence of a longer growing season with a warm Pacific and wetter Southwest has yielded unusual warm, wet springs ideal for tree growth at upper treelines, a surge in woody plant recruitment at all elevations, and the spread of winter-flowering, nonnative grasses such as red brome (*Bromus rubens*) in the Sonoran Desert. Predictions should now revolve around the consequences of a longer growing season during future droughts, which may accelerate adult tree mortality and fire magnitudes, and northward spread of southern species.

Changes in temperatures, rainfall timing, CO_2 and land use: wild speculations on what the future holds for ecosystems of the arid Southwest

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Current models predict that the next decades will have warmer nights, warmer days, wetter summers, drier winters, overall drier years, and higher CO_2. What might this mean for pulse-driven aridland ecosystems? Wild speculation, based on a few facts, might construct the following scenario: within soils, we can expect decomposition rates to increase in summer and decrease in winter; depending on annual dryness, overall rates could either increase or decline. As rates are quite low in winter, this probably means an overall increase. Gaseous loss from the soil (NH_3, NO_x, N_2O, CO_2, CH_4) should also increase, as summer losses dominate this system. Biological soil crusts, which contribute C and N to soils, influence vascular plant germination and success, increase soil stability and C sequestration through increased soil aggregates, and mediate C and N gas fluxes, will be affected by increases in temperature and summer rainfall. Cover will be reduced, resulting in increased soil loss through wind and water erosion, and increased albedo, leading to higher soil temperatures. Species composition will change, accompanied by reduced C and N inputs. On the other hand, increased CO_2 is expected to increase C and N fixation rates. Any shifts in the daily timing of rainfall will also affect C and N inputs. These inputs, in turn, will affect soil food web activity. Thus, soil biotic activity and subsequent decomposition rates will be affected in an unknown way. Reduced frost-heaving will reduce soil surface roughness, leading to decreased water infiltration, seedling establishment and local collection of organic matter. Changes in weather will affect dust input and loss, which will influence soil fertility. Vascular plant communities will be affected both indirectly, through effects on soils, and directly by effects on their physiology. Photosynthesis and respiration rates would increase year-round; however, warmer night temperatures should increase carbon loss when carbon gain is not possible. Increased summer rainfall will favor shrubs that utilize summer rain over those that depend on winter rain. Evidence suggests that exotic annual grasses will increase, bringing larger and more frequent fires with them. Increased land use is expected to exacerbate most of the above changes. Anthropogenic N deposition could either exacerbate or mitigate some of the above effects. So what research opportunities does this situation present? Lots!!! Most important will be interdisciplinary efforts that link the response of hydrologic cycles, soils, and plant communities with expected and realized changes in climate. The biggest unknown, and perhaps the most pivotal, question is how soils will respond. While we know virtually nothing about how they function under current conditions (much less what might happen with climate change), we do know they profoundly influence the structure and function of desert plant communities. As a group, we will discuss ways to address this, as well as other, research topics.

Response of desert riparian ecosystems to potential changes in climate

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Properties and dynamics of desert riparian vegetation are controlled primarily by flood disturbance and spatial and temporal patterns of groundwater depth. Patches of riparian vegetation in the active floodplain represent stages in a dynamic disturbance/regeneration cycle. Climate change has the potential to alter this cycle by changing key hydrogeomorphic factors involved in the establishment, successional development, and ultimate removal of vegetation by scouring flood events. Extended drought may result in loss of some tree species and shifts in dominance to drought tolerant species in streams controlled by runoff and ephemeral recharge. Streams controlled by groundwater discharge would be affected more by changes in the frequency and intensity of floods needed for tree establishment. Other aspects of potential climate change, particularly shifts in summer monsoon activity, can differentially impact the growth and survival of riparian trees. Use of monsoon rains depends on groundwater availability; species that take up monsoon rains do so more readily at sites where groundwater is less available. Riparian ecosystems contribute significantly to basin-level evapotranspiration, and climate change can alter patterns and rates of tree transpiration. Plant processes affecting ecosystem hydrologic balance (e.g., stem water storage, transport resistance, redistribution of water by tree roots) vary by species and tree size. Therefore, climate-driven shifts in species composition, abundance, and forest successional stages will alter hydrologic balance of riparian corridors and whole drainage basins.

The consequence of a warmer, drier climate on base flow in the Upper Verde River

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The Problem

Is the consequence of a warmer, drier climate a reduction in the base flow of perennial streams? Less precipitation would presumably result in proportionately less recharge to aquifers, eventually translating to less base flow in perennial streams over some unknown time scale. The smaller the base flow, the greater the consequence of climate changes, as the water table drops below the streambed and roots of riparian vegetation. The Upper Verde River in north-central Arizona has an average base flow of 25 ft^3/s with mean daily values ranging from 15 to 33 ft^3/s (based on a 36-year record at USGS 09503700). At least 80 percent of base flow in the Upper Verde River (Granite Creek to Perkinsville—a 24-mile reach) emerges from Big Chino Springs, located just downstream from Granite Creek. The aquifers supplying Big Chino Springs lie within the Big Chino watershed (Wirt and Hjalmarson, 2000). The purpose of this presentation is to consider the effects of climate change on the Upper Verde River using a simplified water budget for the Big Chino aquifer that is based on a conceptual model of the available geologic, hydrologic, and isotopic evidence (Wirt and Hjalmarson, 2000).

Background

Base flow in the Upper Verde River is an important source of water that supports riparian plants, fish, and other wildlife, particularly during dry seasons and droughts. Surface water rights of the Verde River are fully allocated, thus any diversion of upstream water results in a deficit for downstream users in Verde Valley and Phoenix. In 1984, Congress declared most of the Verde River—from Camp Verde to Sycamore Creek—a Wild and Scenic River. The Upper Verde River has been designated critical habitat for several threatened and endangered species of native fish, including spikedace minnow, extirpated loach minnow; and recovery populations of razorback chub and Colorado squawfish. The Upper Verde River watershed lies within Yavapai County, the fastest growing rural county in Arizona with a growth rate four times the national average (Woods and Pool Economics, Inc., 1999). Historical ground-water pumping in Big and Little Chino Basins has decreased base flow in the Verde River in the past, and proposed development may result in future declines.

The Approach and Findings

To address this hypothetical problem, real data averaged over time (precipitation, water levels, base-flow discharge, and pumping) are used to examine relations between inflow, outflow, and storage.

Water-budget parameters for the Big Chino aquifer are strongly correlated with changes in river base flow. For example, historical pumping for irrigation and base flow are inversely correlated. To simulate the effect of warmer, drier conditions, it is assumed that an increase in pumping is analogous to a decrease in the quantity of recharge. A second assumption is that the Big Chino aquifer is under steady-state conditions and that storage remains constant. Thirdly, it is assumed that recharge to the aquifer equals discharge to the river, if averaged over a large enough timeframe. This conceptual model is used to make gross estimates of how much water levels and/or recharge could decline before the river dries up.

The ground-water outlet of the Big Chino alluvial basin is through karst features along the trend of the Big Chino Fault, a large basin-bounding fault that juxtaposes limestone bedrock against alluvial and volcanic basin fill. The altitude of Big Chino Springs is about 20-30 feet below the water table near the ground-water outlet in lower Big Chino Valley. Because base flow is supplied predominantly from a single spring network through a narrow bedrock outlet, small changes in the water table of the source aquifer correlate with changes in base flow of the Verde River. For example, on the basis of a 40-year historical record at an index well in lower Big Chino Valley, a 1-ft decrease in water level is correlated with a 1.3 ft^3/s decrease in discharge in the Verde River (coefficient of determination = 0.65). Projecting the slope of the relation beyond the available data intercepts zero discharge in the Verde River at approximately 19 feet. Obviously the effects of climate change on water levels would not be identical at every site, but would be integrated over the entire drainage basin of 1,848 mi^2.

Given that recharge to Big Chino Valley is roughly equal to the discharge of Big Chino Springs (about 14,500 acre-feet) and if recharge were to occur evenly throughout the watershed, this equals 0.16 inch of recharge per year. In reality, rates of recharge often vary spatially by orders of magnitude. Alluvial fans and tributaries to Big Chino Valley draining higher-altitude mountain slopes have the greatest precipitation and potential for recharge along mountain fronts and beneath streambeds. Regions with little rainfall and geologic strata that dip away from Big Chino Valley are unlikely to supply substantial recharge. About 15 percent of Big Chino Valley exceeds an altitude of 6,000 ft—predominantly in the Bradshaw, Santa Maria, and Juniper Mountains (about 280 mi^2). By assuming that recharge only occurs in about 15 percent of the drainage basin, an annual recharge rate of 0.96 inches of water is needed to supply constant discharge to Big Chino Springs. In reality, however, one cannot assume that a one-inch decrease in recharge to major recharge areas would dry up the river immediately, because the aquifer storage term is undetermined, and difficult to measure on a regional scale. The effect of climate change on vegetation and resulting evapo-transpiration is also unknown. Less vegetation could mean lower ET and result in higher base flow (to a certain point); or higher temperatures could result in higher ET and decreasing base flow.

Two additional unresolved issues emerged in the water-budget analysis; lack of information regarding (1) ground-water travel times and (2) the amount of ground water in Big Chino Basin that may have been recharged during the Pleistocene. Because ground-water travel times are unknown, the duration of lag time between the onset of climatic change and a decrease in base flow is unknown. Moreover, ground water in the deeper parts of the basin was likely recharged during cooler, wetter conditions in the Pleistocene. Younger ground water remains near the top of the aquifer and is discharged to wells and springs disproportionately. Thus, in the advent of a warmer and drier climate, the average age of all the ground water discharging from Big Chino Basin would become older. Ongoing work is presently directed at defining ground-water flow paths and determining the age of ground water using carbon-14 and other dating approaches. This information will improve understanding of ground-water recharge and aquifer replenishment in the likelihood of increased pumping or climatic change. This information will be useful to assist future numerical ground-water modeling efforts.

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Predicting vegetation response to climate

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We developed a model for plants in arid ecosystems to determine character combinations that would maximize whole-plant photosynthetic carbon gain under specific climate conditions. The soil was divided into two components, one shallow soil layer with rapidly changing soil moisture content, representing spring and summer moisture input, and the deeper soil layer with a constant soil moisture level, representing water stored after winter recharge. Soil conditions were varied by changing the frequency of rainwater input into the in the shallow soil and by setting different levels of deeper soil moisture. Optimal combinations of 8 morphological and physiological parameters were determined using a genetic algorithm. We show that a drier, warmer climate produces shifts in the optimal character combinations that should modify the dominance relationships of existing vegetation in the desert Southwest. Furthermore, winter drought is shown to require different adaptive responses than summer drought. These predictions are discussed alongside experimental results on the differential sensitivities of plant functional types to winter and summer drought.

Modeling plant assemblages with changing climate

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(not necessarily in that order).

A geospatial interface linking land cover, soil, and topographic data to hydrologic simulation models has been developed for the purposes of investigating the impacts of land cover change on hydrologic response. This tool allows for the automated parameterization of the Soil Water Assessment Tool (SWAT) and the KINematic runoff and EROSion model (KINEROS). Both of these models are affected by changes in land cover, especially with respect to volume runoff and sediment discharge. Several scenarios regarding the impacts of projected climatic change on land cover type and distribution were used to provide input to the simulation models. Results from the simulations indicate projected changes in hydrologic response resulting from land cover transitions due to alterations in the climatic regime of the semi-arid Southwest.

The influence of climate change and fire frequency on root strength and landslide susceptibility in upland forests of the desert southwest

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If forecasts of a hotter and drier climate for the desert southwest are correct, catastrophic drought could increase regional tree mortality as well as the frequency and intensity of fires. At higher elevations in the mountain ranges of the desert southwest, areas covered by a mixture of ponderosa pine, oak woodlands, and mixed coniferous forests, the impact of fire and the resulting conversion of vegetation may lead to decreased root reinforcement within granular soils on steep, landslide-prone hillslopes. During subsequent large magnitude storms, decreased root reinforcement could heighten regional landslide susceptibility. The associated increase in landslide frequency and sediment delivery to channels could impact sedimentation rates on alluvial fans, soil loss from hillslopes, surface water turbidity, as well as public safety, infrastructure, and property.

The previous decades of cooler and wetter climate, a legacy of land management supporting fire suppression, and invasion of nonnative grasses have resulted in increased fuel loading in upland forests. The past cooler and wetter climate has increased woody plant material brought about by a longer growing season and warm, wet Spring seasons. Current forests at higher elevations of the desert southwest affected by anthropogenic influences such as land management supporting fire suppression, livestock grazing, and timber harvests tend to be denser and more spatially uniform, have many more small trees and fewer large trees, and have greater fuel loading. In addition, since the 1970s, nonnative grasses such as red brome (*Bromus madritensis* formerly *rubens*) have spread throughout the desert and become increasingly dominant in native plant communities. Nonnative grasses tend to produce a continuous fuel bed across the landscape and the dried remains of the nonnative grasses stay rooted in highly flammable dense stands for years after they die. The legacy of these influences as well as increased urbanization in the Mojave Desert likely results in an increased fire frequency and spatially continuous completeness of vegetation removal during fires. A shift to a drier and hotter climate would likely accentuate the probability of large, high-severity wildfires in steep, landslide-prone hillslopes.

Vegetation removal and/or conversion arising from fire and timber harvesting are thought to have similar impacts on root reinforcement in granular soils. Detailed measurements of suppressed root cohesion within industrial forests of the Oregon Coast Range, for example, reveal that the disturbance legacy arising from fire, commercial thinning of timber, or partial conversion of coniferous to hardwood species can last for greater than a century. Root characteristics in industrial forests display lower root densities within the soil, lower root cohesion, smaller diameters, and different species assemblages than forests without anthropogenic influences. The associated decrease in root cohesion arising from climate change is likely to have similar long-lived and dramatic influence on root characteristics.

Landslide initiation within shallow forest soils, is governed by numerous factors including: hydrology, topography, and material properties (e.g., cohesive reinforcement from vegetation). The GIS-based slope stability model (SHALSTAB), a steady-state runoff approximation that incorporates the topographic influence on subsurface discharge within hillslopes and hence the positive pore pressure distribution, is used to estimate regional landslide susceptibility from the topographic signature. The influence of future catastrophic drought on landslide susceptibility is evaluated using the model SHALSTAB by simulating the influence of a regional decrease in root cohesion enhanced tree mortality and fire magnitudes.

Although SHALSTAB can be used to estimate the regional landscape response, the site-specific spatial variability in vegetation and associated root strength can only be obtained from other methods. That is, the local root strength exhibits considerable spatial and temporal heterogeneity arises from the mosaic of vegetation with a continual turnover of individuals and species in response to local growing conditions and disturbance history. Although simple stand age classifications may not adequately reflect root reinforcement, promising techniques are emerging to compare the spatial extent and temporal frequency of stand-resetting disturbances at a regional scale with ≤ 30 m resolution. In addition to aerial photograph interpretations and species composition data, remote sensing techniques can be used to characterize both the land surface and vegetation canopy structure. For example, time series analyses of Landsat imagery and airborne laser altimetry can be incorporated into slope stability models to predict relative landslide susceptibility based upon the local vegetation condition in response to changing climate and fire frequency.

Analysis of basin recharge susceptibility to drought in the desert Southwest using numerical and GIS-based models

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The purpose of this study is to develop a new method of basin characterization that allows inter-basin comparison of recharge mechanisms and recharge potential under current, wetter and drier climates. This simple GIS-based analysis is then compared to other methods of estimating recharge, particularly the Maxey-Eakin method and a numerical rainfall-runoff model.

Introduction

The Death Valley region is used in a preliminary analysis to determine the feasibility of using this new method because of the ability to compare it to previous analyses. Death Valley region is primarily in the northern Mojave Desert, but extends into the Great Basin Desert, and is in the rain shadow of the Sierra Nevada. Elevations range from 86 m below sea level at Death Valley to 3,600 m above sea level in the Spring Mountains. Thirty-eight basins characterized by Harrill and Prudic (1998) lie within the Death Valley region (Fig. 1) and will be used to estimate recharge mechanisms and recharge potential using the GIS-based method and can be compared to the Maxey-Eakin method and the numerical rainfall-runoff model.

Net infiltration and recharge have been estimated by previous investigators for the areas within the Death Valley region using methods such as water-balance and soil physics techniques, geochemistry (chloride mass balance), and transfer equations based on other variables (such as precipitation using the Maxey-Eakin method).

Under steady-state conditions, net infiltration becomes recharge except when perched water is discharged in springs and lost to evapotranspiration. Travel time through the unsaturated zone is controlled by net infiltration, unsaturated zone thickness, and effective flow-pathway porosity. As climate changes, the travel time of infiltrating water through the unsaturated zone may change, as well as the spatial variability of recharge. Recharge occurring today is spatially variable due to alluvium thickness, subsurface features, unsaturated zone thickness, layering and properties of geologic and sediment strata, and is dependent on the net infiltration at each point which responds to the variables influencing recharge over time scales of years to centuries.

A conceptual model of net infiltration is essential for developing the GIS-based model of recharge. The conceptual model of recharge for a basin can be simplified to identify the areas within the basin where recharge processes are initiated. Net infiltration does not occur at every location in a basin nor does it occur every year. It is likely that the majority of the area contributing to recharge is a relatively small portion of the basin and years with above average precipitation provide the most recharge. The GIS model is used to identify those areas that would either recharge directly or lead to runoff, which could recharge down stream.

On a yearly basis potential evapotranspiration exceeds precipitation. However, on a monthly basis and in certain areas of a basin, precipitation exceeds evapotranspiration and storage, and net infiltration and/or runoff occur, depending on the rate of rainfall or snow melt, and the soil and bedrock permeability. The conceptual model assumes that all processes controlling net infiltration occur within the top 6 m of the surficial matertials. The GIS model uses spatial estimates of precipitation (Figure 2), temperature, potential evapotranspiration, soil storage, bedrock permeability and soil infiltration capacity to determine the area in a basin where excess water is available and the amount that is available to recharge directly or runoff and become mountain front recharge or ephemeral stream recharge downstream in the alluvial basin.

The other question to be addressed is the timing of recharge after net infiltration occurs. It is quite likely that climate change over the next 20 years will change the net infiltration values both spatially and temporally. It is also likely that some basins will not see a change in recharge related to this climate change for hundreds or thousands of years. Therefore, an analysis of unsaturated zone travel time is needed to determine when changes in surface processes will be reflected at the water table.

Methods

Regional estimates of average annual and monthly precipitation are made by using existing meteorological data for the Death Valley region. These values are distributed from the measuring station using a combined inverse distance squared method and an elevation correlation. A similar method was used to estimate minimum, maximum and mean monthly temperatures. In addition, one and two standard deviations were calculated for both precipitation and air temperature to use as estimate of wetter and drier, and warmer and colder conditions to simulate different climates.

Soil storage capacity and soil infiltration capacity were estimated by using the STATSGO soils database. Soil thickness was estimated using the STATSGO soils database, surficial geologic mapping and topographic position. Bedrock permeability was estimated using a surficial geologic map and literature values for the estimation of permeability based on geologic material.

Potential evapotranspiration was estimated using a computer program that calculates solar radiation for each grid cell in the basin (279 x 279 m), converts it to net radiation and soil heat flux, which is used in the Priestly-Taylor evapotranspiration equation.

Snow is calculated for areas where precipitation occurs and air temperature is below freezing. Sublimation of snow is calculated as a percentage of potential evapotranspiration and snowmelt is based on solar radiation load when air temperatures are above freezing.

A series of equations are developed to calculate the area and amount of potential recharge. For example, each grid cell is analyzed for each month to determine water availability for recharge:

Precipitation + snow melt – potential evapotranspiration – snow accumlation – soil storage (1)

If this results in a positive number then that grid cell has the potential to recharge directly or cause runoff to occur which can recharge down stream. In addition, bedrock permeability (K) is added in another equation to determine the possible mechanisms of recharge:

If K >excess water then mountain block recharge = K (2)

If K < excess water then mountain block recharge = K and runoff = excess water – K(3)

The quantity of runoff versus mountain block recharge determines whether mountain front or ephemeral stream recharge dominates. The number of grid cells that provide direct net infiltration, or provide runoff can be used to compare basins.

The model is used for both current precipitation estimates and 1 standard deviation above and below the current values. This allows for the determination of the relative amount and mechanisms that would dominate under wetter or drier climatic conditions. In addition drier and warmer conditions are applied to determine the presence of snow accumulation. Snow accumulation can become a critical term as it delays the application of water to the surface thus extending the possibility that in the following month precipitation and snow melt will combine to exceed the storage capacity of the soil causing net infiltration and/or runoff.

The basin analysis is being compared to the Maxey-Eakin recharge estimates from Harrill and Prudic (1998), and a numerical rainfall-runoff model. Maxey-Eakin calculates recharge as a percentage of the precipitation falling within a basin. The numerical rainfall-runoff model is quasi three-dimensional and uses quasi mass-balance processes, real or stochastically simulated precipitation, the physical setting, and hydrologic properties of the site to approximate the actual conditions. The grid blocks for this analysis are at the same scale as the GIS-based model.

The unsaturated zone travel time is calculated as $(\phi_{eff} \text{ x } Z_{uz})/ I_{net}$, where ϕ_{eff} is effective unsaturated zone porosity (m/m), Z_{uz} is the thickness of the unsaturated zone (m), and I_{net} is net infiltration (m/yr). Estimates of unsaturated-zone thickness for the region are based on the difference between digital elevation maps and ground-water elevations. Thickness of the unsaturated zone for the region ranges from 0 to 2000 m. The effective unsaturated zone porosity is the most difficult parameter to assess and requires detailed geologic maps from the surface to the water table. In addition, estimates of subsurface bedrock permeability, in the matrix or in the fractures, is also needed. This information is just now becoming available and only estimates of travel time can presently be made.

Results

Net infiltration is a function of precipitation, air temperature, soil thickness, and bedrock permeability. Present-day net infiltration is assumed to be equivalent to potential future recharge on a regional basis but delayed by travel time through the unsaturated zone. The GIS method provides a simple, straight-forward method to compare the potential for net infiltration between basins for current or different climates. Under yearly average climatic conditions very little recharge occurs within the Death Valley region. However under wetter than average conditions the amount and areal distribution of recharge greatly increases. Under drier and warmer than average conditions less net infiltration occurs overall and less snow accumulates in the higher elevations greatly reducing the potential for mountain block and mountain front recharge.

Forecasting landscape response of the Mojave Desert to future climate variability

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Accurately predicting future climate variability by regional circulation models, especially when forecasting human effects, is a daunting problem, but even if detailed prediction were possible we would not be able to accurately forecast the *effects* of future variability on the Mojave Desert. We cannot accurately forecast climate effects on the desert landscape because we lack knowledge of how climate has varied since the last glacial maximum, whether the time period in question is the Little Ice Age or a single El Nino season, and what effects those variations had on the landscape. Basic needs for forecasting landscape response from a geological perspective include: (1) properties of surficial materials, (2) how the landscape responds to modern climate variability and human impacts, and (3) how the climate and human impacts have varied in the past. These basic needs are most effectively understood, and that understanding is most readily extrapolated, by quantifying the properties of surface materials and welding that information with study of landscape processes and climate as a function of time. Such understanding can lead to landscape response models, calibrated by past landscape responses on several temporal and spatial scales, which should be an effective tool for predicting future landscape response.

The Recoverability and Vulnerability of Desert Ecosystems project and other projects are focusing several studies toward developing the basic information that will permit landscape response modeling. Results from some of these studies are being reported in this workshop. We summarize below results from several other studies.

A fundamental study is characterizing materials in the context of geomorphic process, age, and soil development, using field studies and remote sensing research. These geomorphic and material attributes, when combined with laboratory determinations of particle size (sampled as a function of depth) will be used in deterministic models to estimate texture of surface materials. Texture in turn is valuable for modeling a number of processes, and can be calibrated to soil moisture properties that will permit prediction of soil moisture for future climate. Results to date include characterizing material properties of alluvial fans with differing source rock characteristics, and modeling soil moisture response to rainfall.

Geomorphic process studies will lead to process models that can incorporate variables from models of future climate. For instance, mingled eolian sand and alluvial fan deposits can be sensitive to climate variability and disturbance, which would cause rapid changes to vegetation and animals in this widespread desert ecotone.

Preliminary results indicate dramatic biologic changes associated with proportion of eolian sand, but work to quantify rates of change with human impacts and changing climate variables remains.

Our approach to determining the effects of millennial-scale climate variability is to date major landscape-influencing geomorphic events and to quantify sediment flux in several geomorphic environments as a function of time. Results to date show that a major debris flow in the Silurian Valley was emplaced on a distal fan about 5 to 6 ka, at a time when many fluvial deposits were emplaced on adjacent fans. Despite the activity of the fans, the axial drainage of Silurian Valley aggraded only for a short period and returned rapidly to its former channel, implying impressive long-term stability. Elsewhere, groundwater-discharge deposits dated at about 13 ka are overlain by a sheet of eolian sand, indicating dramatic changes in local conditions in the latest Pleistocene. These data, when accumulated over a broad area, will lead to new understandings of landscape activity on a centennial to millennial scale, which can be related to climate changes to offer better insight into climate-landscape process links.

Human impacts to the landscape may be exacerbated by climate changes, but are more difficult to quantify than natural processes because the impacts have accrued over thousands of years as technologies changed, and most impacts were not recorded. One approach for evaluating effects of climate variability on future impacts is to model impacts as a function of climate variables. An example is mapping susceptibility to soil compaction (based on laboratory compaction studies) that evaluates susceptibility as a function of soil moisture. Changes in soil moisture cycles associated with forecasted climate may alter the time periods of maximum susceptibility. Similar approaches can be developed for susceptibility to erosion as a function of rainfall amount and intensity, and many other examples.

All of these studies are initial efforts that require testing, reformulation, and retesting until they accurately predict desert landscape conditions and process response. A few years of intensive studies probably will greatly clarify millennial-scale climate variability and the attendant kilometer-scale geomorphic response. Establishing material properties, climate history, and process response models at decadal to seasonal temporal scale and decameter spatial scale will require a much longer sustained effort. Identifying those processes most sensitive to the short-term climate variability predicted by circulation models, such as eolian sand sheet movement, perhaps will be the most fruitful approach.

Carbon Sequestration in Arid and Semiarid Ecosystems of the Southwestern United States: Implications for Predicted Warmer and Drier Conditions in the Next 20 Years

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International concern about global warming has resulted in proposed treaties with the intent of lowering carbon dioxide and methane emissions. Industrialized nations such as the United States must either reduce emissions or declare “carbon credits,” which is carbon sequestered from the atmosphere in natural ecosystems or agricultural lands. No consideration has been made of changes in carbon sequestration in most natural ecosystems, particularly those in the arid and semiarid southwestern United States. In addition to the impacts of global carbon cycling, concerns are repeatedly raised on a regional scale about changes in natural landscapes of this region, particularly in riparian ecosystems. The conventional wisdom expressed repeatedly in the news media, as well as certain scientific and conservation organizations, is that the amount of riparian areas has decreased by between 50 and 95%. Other common concerns are the “degradation” of desert grasslands by establishment of woody shrubs and trees (Wilson et al., in press); the downslope movement of junipers onto rangelands (Rogers, 1982); and whether anthropogenically-driven directional change is occurring in desert ecosystems.

Directional changes in species composition of Southwestern rangelands have been documented throughout the 20th century. Change has occurred irrespective of land-use practices (Turner, 1990; Webb, 1996). In all cases, woody vegetation with C3 photosynthetic pathways have expanded, sometimes at the expense of C4 grasses (Wilson et al., in press) but in other cases into previously unoccupied habitat (Webb, 1996). In an update of Hastings and Turner (1965), Turner et al. (unpublished data) have found large increases in biomass depicted in repeat photography, particularly between the 1960s and 1990s. The conversion of rangeland to woody C3 species has continued despite overall reduction in livestock grazing intensity in the latter part of the 20th century. Despite real concerns about removal of wetlands, riparian vegetation has dramatically increased – not decreased – in most riverine habitats of the Southwest, particularly after 1960 (Webb, unpublished data). Biomass in common Mojave Desert xeric ecosystems (particularly ones dominated by *Larrea tridentata*) have increased by a factor of 2-4 on the Nevada Test Site (Webb et al., unpublished data). The expansion of C3 species appears to cross ecological types in the Southwest and northern Mexico and may result from the three interrelated effects of (1) increased winter precipitation that occurred particularly after 1975 (Wilson et al., in press); (2) increased winter temperatures, particularly minimums; and (3) increased atmospheric CO_2 (Bazzaz, 1990). Irrespective of the reason, considerable amounts of carbon are being stored in C3 plants in the region.

No attempts have been made to estimate the amount of carbon sequestered in plant biomass over the region using anything remotely approaching an ecosystem-based technique. Several methods can be used to quantify density, cover, and(or) biomass increases, but usually these methods are applied to small, permanent vegetation plots (Beatley, 1980; Goldberg and

Turner, 1984). Permanent plots can be used to quantitatively document long-term vegetation changes, but their small size and local conditions at the plots may reduce their regional representation. Systems of regional plots, which typically are designed to monitor single-species changes, are one way to scale plot data to larger land areas (Pierson and Turner, 1998).

Several larger-scale methods are used to assess the magnitude of long-term changes in arid and semiarid ecosystems. Remote sensing using satellite-based platforms can assess change from as early as 1974 to the present (Kepner et al., 2000) but can only detect habitat change, not species specific changes. Aerial photography is commonly used to assess changes in vegetation cover and is available over most of the Southwest from 1935 to the present, but like satellite-based imagery, aerial photogrammetry is limited to assessment of broad changes. Repeat photography can be used to assess species-specific changes following settlement in the late 19th century, unlike satellite- or aircraft-based imagery, and historical photography is widespread in the region. Large numbers of repeat photographs, and particularly time series photography at specific locations, are required to offset the lack of spatial coverage in each image.

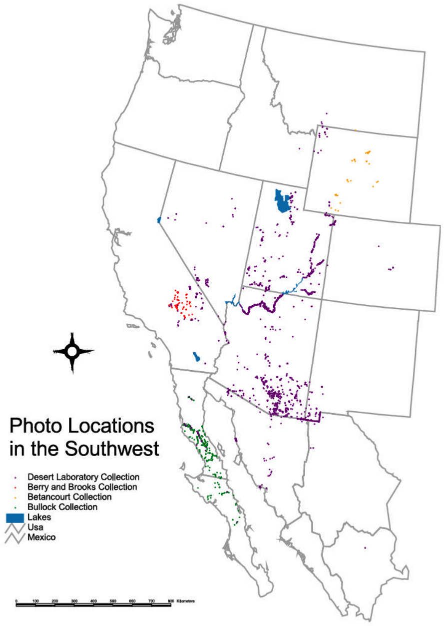

Fig. 1. Locations of repeat photography camera stations in the southwestern United States and northern Mexico.

Table 1. Listing of repeat photography by region in the southwestern United States.

Description	Number of Photos
Total Desert Lab Collection	4707
Collaborator Photos	559
Major rivers in region	2096
Mojave Desert	391
Great Basin Desert	311
Sonoran Desert	1615
Colorado Plateau	157
Chihuahuan Desert	137
Baja California	401

The Desert Laboratory Repeat Photography Collection, combined with related efforts in the region (Fig. 1), provides an ideal technique for assessing carbon sequestration in arid and semiarid ecosystems. At present, the aggregate collection contains 5,266 camera stations in most of the region's ecosystems (Table 1), excluding higher-elevation forests. The motivation for building this collection, which was done over a 40-year period by USGS and Mexican-government scientists, was to document long-term landscape changes in the desert regions, including changes in plant biomass. We hypothesize that the amount of carbon sequestered in arid and semiarid ecosystems has increased in the 20th century in the southwestern United States, particularly since 1960. This biomass increase has occurred despite development and pressures on ecosystems, such as grazing and logging. Increases in winter precipitation and temperatures, as well as increases in atmospheric carbon dioxide, are the probable reasons why carbon is increasingly sequestered in nearly all the vegetation alliances of the region.

The predicted shift to warmer and drier climates is based on an analogy to conditions between about 1942 and 1975 in the southwestern United States. Because our photographs closely span this period, we have some basis for speculation on how the predicted climate shift may affect carbon sequestration. Pressures on surface-water and ground-water systems will largely drive overall changes in riparian ecosystems, although lack of winter floods and decreased winter precipitation will likely minimize recruitment along natural watercourses. The recent increases in C3 plants, particularly in desert grasslands, may slow. Increased winter temperatures may increase the potential for C3 seedling survival, although fewer seedlings are expected to germinate owing to decreased precipitation. Drought pruning likely will reverse the trend in carbon sequestration, but decreases in soil moisture may decrease decomposition rates, resulting in carbon stored as litter with little net change in carbon sequestration.

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Changing Climate and Extreme Floods

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Over the past 20 years the natural archive of extreme floods in the Southwest U.S. has yielded records extending centuries and millennia into the past. There are now scores of such records, on rivers and streams throughout the region. The paleoflood hydrological interpretation of these records has revealed that periods of wet and dry climate are paralleled by periods of higher and lower flood variability. The paleoflood record indicates the clustered occurrence of the largest floods actually to have occurred in such periods. Because these floods represent extreme conditions for flood generating storms and for physiographic controls, they provide limits on what can be expected for altered storm regimes associated with changed climate. Conventional flood-frequency analysis may entail highly problematic difficulties when used to extend the modern streamflow database to changed climate regimes. Paleoflood data are thus absolutely essential for the responsible applied science of understanding and adapting to changed flood phenomena associated with changed climate.