REGIONAL PATTERNS OF PLANT COMMUNITY RESPONSE TO CHANGES IN WATER: OWENS VALLEY, CALIFORNIA

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Abstract. The conversion of large natural basins to managed watersheds for the purpose of providing water to urban centers has had a negative impact on semiarid ecosystems, worldwide. We view semiarid plant communities as being adapted to short, regular periods of drought; however, human induced changes in the water balance often remove these systems from the range of natural variability that has been historically established. This article explores vegetation changes over a 13-yr period for an entire water management area in eastern California. Using remotely sensed measurements of vegetation live cover, a recent vegetation map, field data and observations, precipitation records, and data on water table depth, we characterize the responses of xeric, phreatophytic, and exotic Great Basin plant communities. Despite the complexity of plant communities and land-use history, our technique was successful in identifying discrete modes of response. Differences in vegetation response were attributable to available groundwater resources (modified by water management activities), annual precipitation, and land cultivation history. Fifty-one percent of our study area, including phreatophytic and xeric communities, showed unchanging vegetation conditions and had experienced relatively minimal human disturbance. Nineteen percent of the area exhibited a linear decline in live cover during a drought when ground-water pumping lowered water tables. In portions of these areas, the decline in native phreatophytic cover was followed by an increase in exotic, nonphreatophytic species when the drought ended; in the remainder, cover was suppressed. Finally, vast regions that had been significantly disturbed showed live cover changes that were amplified with respect to precipitation, indicating the presence of exotic annuals. We view the increase in exotic species across the entire study area to be indicative of a fundamental shift in ecosystem function from one buffered from drought by stable ground water conditions to one sensitive to small changes in precipitation. The tools and techniques used here are applicable wherever large regions of land are being managed in an era of changing environmental conditions.

Key words: exotic annuals; Great Basin; land-use/land-cover change; Owens Valley, California; phreatophytic plants; remote sensing; water resources.

INTRODUCTION

Diversion, exportation, and inter-basin transfers of water within arid environments have increased in frequency and quantity over the past century. Naturally flowing waterways and untapped aquifers are increasingly rare, and water extraction has led to regional groundwater depletion in many areas, worldwide. These practices typically result in adverse ecological impacts to aquatic, riparian, wetland, mesic, and phreatophytic systems naturally dependent on that water (Davies et al. 1992, Naiman et al. 1993, Naiman and Turner 2000, Postel 2000). Climate change projections for the next century predict that annual precipitation patterns may change dramatically (IPCC 2001). Precipitation is likely to become more unevenly distributed spatially and temporally making it necessary for water managers to increase water storage during wet periods

then increase extraction during dry periods (Field et al. 1999). Such changes could result in further decoupling of water resources from natural systems already stressed by human water extraction. In regions where extraction exceeds recharge, balancing the need for water against the conservation of natural ecosystems presents a daunting challenge.

Numerous studies have documented the detrimental effects of hydrologic alterations on vegetation (e.g., Smith et al. 1991, Stromberg and Patten 1992, Busch and Smith 1995, Nilsson and Berggren 2000, Vandersande et al. 2001). Nevertheless, most studies occurred relatively recently (Rosenberg et al. 2000). Therefore, few have directly influenced existing water management policies, and hydrologic alterations designed to provide water for power, agriculture, or urban use often disregard the long term consequences of changes in surface and groundwater availability on vegetation and other community processes at or near the point of origin (Pringle 2000). With a few exceptions (e.g., Stromberg et al. 1996, Castelli et al. 2000, Horton et al. 2001),

most studies of the effects of hydrologic alterations on vegetation have examined impacts in riparian, spring, or obvious wetland areas. Few studies have monitored long term changes throughout broader areas within watersheds. Away from riparian zones, old terraces, basins, flats, and parts of alluvial fans often contain phreatophytic species dependent on groundwater for sustained biomass and recruitment (Bryan 1928, Sorenson et al. 1991, Or and Groeneveld 1994, Le Maitre et al. 1999).

Water use decisions often affect large portions of land, and the breadth of the resulting impacts are difficult to characterize using a small number of field sites. To better understand the magnitude of water management decisions, we must broaden our field of view to entire landscapes, then incorporate the best available data on environmental parameters to construct mechanistic models. With the advent of satellite data to record conditions such as vegetation cover, a wealth of a posteriori information has become readily available. The merits of using remote sensing data for regional analyses of vegetation are generally recognized (Woodwell et al. 1984, Tueller 1987, Woodward 1996). However, researchers using these data must account for the vegetation response by assembling and analyzing data on pertinent environmental conditions. Through the process of collecting regional-scale environmental data and analyzing them with remote sensing data, we have the potential to extend our field-site-based understanding of vegetation response to the regional scale.

Prior to developing models of vegetation change due to water management decisions, vegetation changes that have occurred in the absence of anthropogenic influences must be considered. Literature supports the hypothesis that relatively intact semiarid vegetation is tolerant of drought in the absence of anthropogenic effects. For example, native vegetation in arid and semiarid regions responds somewhat predictably to variations in annual precipitation (Beatley 1974, 1975). Data from tree rings, lake cores, and pack-rat middens in the Eastern Sierra (California) show that over the past 1000 yr the region has experienced 10- to 50-yr droughts regularly, as well as single-year extreme events (Graumlich 1993, Li et al. 2000), yet vegetation communities have remained relatively static (Koehler and Anderson 1995). Changes in natural vegetation that have occurred as the result of climate change typically occur slowly as species gradually expand, reduce, or otherwise alter their ranges (e.g., Tausch and Nowak 1999, Rowlands and Brian 2001). Over the last decade, field measurements of Owens Valley, California vegetation by Manning (2001) showed vegetation to be relatively static in areas where anthropogenic modification was minimal.

Vegetation stability can be disrupted by many anthropogenic factors, including burning, fire suppression, livestock grazing, hydrologic alterations, cultivation, and nonnative species introductions. Our study focuses on the effects of hydrologic alterations, cultivation, and the associated colonization and spread of exotic species. Other researchers have documented adverse changes in phreatophytic and riparian vegetation affected by declining water tables (e.g., Bryan 1928, Sorenson et al. 1991, Stromberg et al. 1996, Le Maitre et al. 1999, Manning 2001). Therefore, we expect changes to occur in phreatophytic communities where groundwater levels are manipulated. Agricultural practices often result in the introduction and spread of exotic species through disturbance and supplemental inputs of water and nutrients to the surrounding plant communities. Vast regions in the intermountain western United States have been invaded by exotic species that evolved under different selective pressures and as a result use resources and respond to climate patterns in novel ways (Young et al. 1972, West and Young 2000).

Owens Valley, California is an intensively managed basin east of the Sierra Nevada Range. The Los Angeles Department of Water and Power (LADWP) exports surface and groundwater 400 km south to Los Angeles via the LA Aqueduct. Recognizing the potential threat to the valley's environment, the Inyo County Water Department (ICWD) began monitoring LADWP's water gathering activities in the mid-1980s through a characterization of changes in vegetation cover and composition, depth to groundwater, and precipitation. In this paper, we examine these monitoring data in conjunction with a remote sensing derived database of percent live cover (%LC) also dating from the mid-1980s (Elmore et al. 2000). The objectives of this study are to integrate remotely sensed data with detailed field measurements, observations, and historical data to identify regional patterns of vegetation change and to determine the extent to which climate and hydrology can explain those patterns.

SITE DESCRIPTION

Natural setting

Owens Valley is a hydrologically closed basin in eastern California. The valley extends ~120 km from north to south and is bordered on the west by the Sierra Nevada and east by the White-Inyo Range (Fig. 1). Naturally, water drains from the mountains to the Owens River. Prior to LADWP water diversions, Owens River flowed to its terminus at Owens Lake. The Sierra Nevada forms a rain barrier, effectively diminishing precipitation from most winter storms. Median annual precipitation recorded at Independence near the center of the valley is 13 cm. Each spring and summer, however, abundant runoff from the melting Sierra Nevada snow pack flows into the valley and recharges groundwater aquifers. As a result, the groundwater table on the valley floor is typically high (Hollett et al. 1991).

Floristically and climatically, Owens Valley straddles the boundary between the Great Basin and Mojave
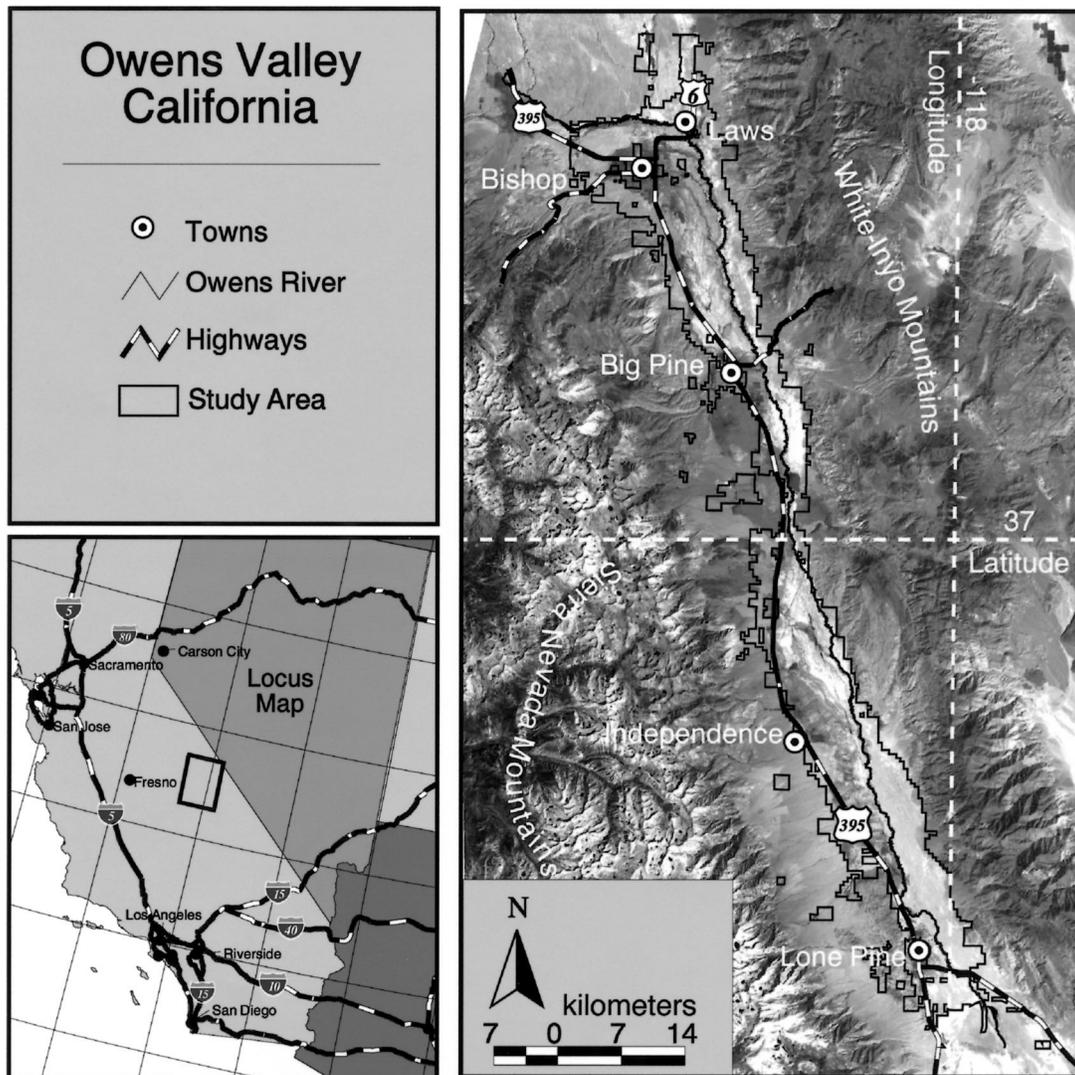
FIG. 1. Location of Owens Valley, California, and map of study area and major features.

Deserts. To best characterize the vegetation, we divide the valley into two broad regions: (1) alluvial fan, a sloping region with typically deep water tables dominated by Mojavean and Great Basin xeric species, and (2) valley floor, a relatively large (61 500 ha), flat, high-water-table basin dominated by phreatophytes (Fig. 2). LADWP owns nearly all land on the valley floor and lower alluvial fans. Vegetation mapping performed by LADWP during the mid- 1980s distinguished a variety of plant communities as occurring in the valley (City of Los Angeles and County of Inyo 1990a). These data were further analyzed by Manning (1997) and prominent features are discussed below.

Seven plant communities dominated by relatively low cover of xeric species were identified, and combined, they account for 34% of LADWP's land area (Table 1). Most xeric community parcels occur on the lower alluvial fans, but pockets of ''shadscale scrub'' and ''Great Basin mixed woody scrub'' are interspersed with meadows and phreatophytic scrub sites on the valley floor, where they typically occupy old terraces or dunes. Two plant communities identified as xeric, ''big sagebrush'' and ''desert saltbush scrub,'' commonly establish on deep groundwater areas previously cleared for agriculture or other reasons.

Four phreatophytic scrub communities were identified, and they occupy 30% of the valley floor (Table 1). One of these, ''rabbitbrush scrub,'' often establishes on abandoned cropland. Total cover averages 15%, rabbitbrush (*Chrysothamnus nauseosus*) is the most abundant species, and the community is classified as phreatophytic by local land managers (depth to water averages 3.9 m). It has since been recognized that at least two subspecies of *C. nauseosus* occur in Owens Valley: *C. n.* ssp. *consimilis* and *C. n.* ssp. *hololeucus*. In addition to differences in floral morphology, *consimilis*
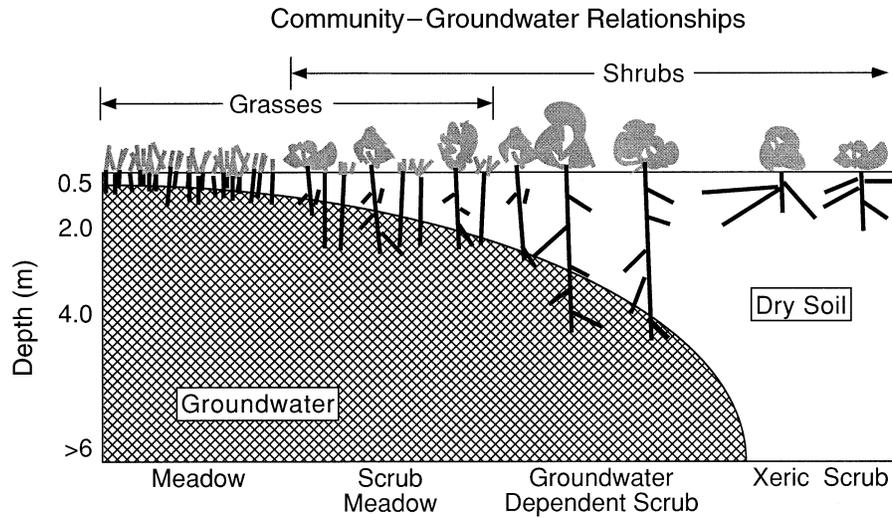
Community–Groundwater Relationships

FIG. 2. Phreatophytic plant communities in Owens Valley are distributed on the landscape according to patterns of groundwater availability. Meadow communities require shallow water tables, a mixture of shrubs and grasses occur at intermediate water table depths, and shrubs dominate the deepest levels. Xeric shrub communities, as defined here, require no groundwater resources. Exotic annuals can compete with varying success at any point on this gradient.

is characterized as growing in poorly drained alkaline soils in valleys, whereas *hololeucus* occurs on well-drained uplands (Anderson 1986, Hickman 1993). Subspecies *hololeucus* is not known to be phreatophytic, and it is commonly found in parcels classified as rabbitbrush scrub. Because no comprehensive study has been performed on the distribution of different *C. nauseosus* subspecies, we continue to include rabbitbrush scrub with the phreatophytic scrub communities. "Nevada saltbush scrub" communities average 20% cover, are located in regions with an average depth to water of 2.9 m, and are dominated by a near monoculture of Nevada saltbush (*Atriplex lentiformis* ssp. *torreyi*), a native phreatophytic shrub. "Greasewood scrub" is a widespread, low cover, intermountain vegetation type dominated by greasewood, *Sarcobatus vermiculatus*, which is a phreatophytic shrub. Average depth to water below greasewood scrub communities is 3.4 m. Shadscale, *Atriplex confertifolia*, a nonphreatophytic species, often grows in association with greasewood at these sites, and other succulent members of the Chenopodiaceae typically occur. Contrary to its name, species dominance in "Owens Valley desert sink scrub" is shared equally by native shrubs and grasses. Although low in cover, species diversity is relatively high. Phreatophytes such as alkali sacaton grass (*Sporobolus airoides*) and greasewood dominate these sites, but nonphreatophytic species are also abundant. Average depth to water for desert sink scrub communities is 2.3 m.

Grass dominated meadow communities comprised 24% of the LADWP lands. The most frequently mapped community type is "alkali meadow" (Table 1), and it is dominated by phreatophytic saltgrass (*Distichlis spicata*), alkali sacaton, or both species. Cover averages 38% for alkali meadow, but ranges from 8% to 85%. As their names suggest, "rabbitbrush meadow" and "Nevada saltbush meadow" are alkali meadows in which the two respective shrubs have become dominant. Average cover and range in cover for these shrub-invaded meadows is lower than for alkali meadows. "Rush/sedge meadow" averages relatively high cover and is dominated by saltgrass and wirerush (*Juncus balticus*). Rush/sedge meadows are typically low-lying areas that are occasionally irrigated directly or indirectly (e.g., via tail water from irrigated fields or seepage from waterways). Mid-1980s average water table depths beneath the four major meadow communities averaged from 2 to 2.4 m. Densely vegetated marsh and riparian communities occur near water sources such as Owens River and active springs. These highly visible and ecologically important communities were mapped as covering only 3% of LADWP lands.

Differences in phenology occur between xeric and phreatophytic communities. With a few exceptions (e.g., sagebrush, *Artemisia tridentata*), many of the common xeric species grow and flower in the spring, then persist through the summer in a dormant state. Growth of phreatophytic shrubs and grasses typically begins in spring, and peak leaf area is achieved in early summer. The phreatophytic species flower in mid-summer, making use of available groundwater, and remain physiologically active until the first frost in early autumn. Because most precipitation occurs in winter, most native annual species flourish and complete their life cycles in the spring of wetter years. In contrast, the major exotic annual species continue growing in summer, flowering and setting seed in late summer.

Many areas that were previously cultivated have been recolonized by native shrubs; however, ~2498 ha

TABLE 1. Plant communities as defined during a 1984–1987 vegetation survey performed by the Los Angeles Department of Water and Power on their land holdings in Owens Valley.

Plant community†	Exotics?	Cultivated?	Parcels (no.)	Area (ha)
Nonnative and miscellaneous lands (10.0%)				
Irrigated agriculture		C	220	4368
Abandoned agriculture, barren	X	C	80	2498
Urban		C	68	910
Permanent lakes and reservoirs			8	158
Intermittent ponds			20	755
Nonnative meadow		C	11	206
Alkali playa			154	154
Xeric scrub (33.6%)				
Mojave creosote bush scrub			11	223
Mojave mixed woody scrub			49	3628
Blackbrush scrub			30	1587
Great Basin mixed scrub			232	11 202
Big sagebrush scrub		C	78	3870
Desert saltbush scrub	X	C	38	1355
Shadscale scrub			112	8453
Phreatophytic scrub (29.9%)				
Rabbitbrush scrub	X	C	82	3900
Nevada saltbush scrub	X	C	85	3330
Desert sink	X		199	9298
Desert greasewood scrub			89	10 501
Meadow (23.6%)				
Alkali meadow	X		479	17 764
Rabbitbrush meadow			29	747
Nevada saltbush meadow			33	1341
Rush/sedge meadow			67	1452
Alkali seep			1	8
Marsh (0.3%)				
Transmontane alkali marsh			13	281
Riparian (2.6%)				
Modoc-Great Basin cottonwood/willow riparian forest			12	818
Mojave riparian forest			13	399
Modoc-Great Basin riparian scrub			29	819
Tamarisk scrub			15	267
Woodland (0.01%)				
Black locust woodland		C	2	8

Notes: Plant communities in which annual exotic species were sometimes dominant are noted with ''X.'' Cultivated sites and community types that colonize following cultivation are noted with ''C.''

† Plant community names follow Holland (1986).

remained virtually barren (with <5%LC perennial native species when mapped) and are now dominated in wet years by exotic annuals such as bassia (*Bassia hyssopifolia*) and Russian thistle (*Salsola tragus*). These areas were classified as ''abandoned agriculture'' (Table 1). A few parcels classified as other community types were actually dominated by exotic annual species. Table 1 lists plant communities in which exotic annuals, specifically bassia or Russian thistle, were dominant in some parcels.

Land and water management history

In Owens Valley, typical plant distribution patterns following environmental gradients such as topography, water table, salinity, and temperature have been dis-rupted by recent and historical land use. Following settlement in 1861, total cultivated and irrigated pastureland increased until about 1920. Water was diverted from Owens River to supply this development (Sauder 1994). Census figures from 1920 showed the greatest extent of agricultural development, reporting 9300 ha of cultivated land and 21 700 ha of irrigated pasture (Vorster 1992). Croplands dominated the northern valley, near the town of Bishop, and livestock grazing occurred throughout the valley.

In 1913, LADWP completed construction of its aqueduct, which diverted water from Owens River and its tributaries and exported it out of the valley to Los Angeles. By the mid-1930s, LADWP had purchased most of the land and water rights in the valley and local
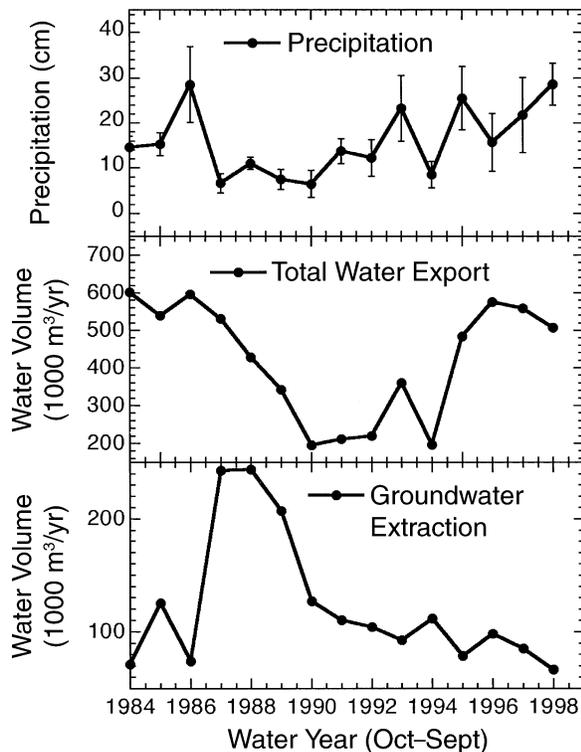
FIG. 3. Recent timeline for Owens Valley showing average annual precipitation (six gauges), total water export, and total water extracted from groundwater resources. A pronounced drought between 1987 and 1992 is exhibited explicitly or implicitly in all three quantities. As an indication of the scarcity of water between 1987 and 1992, groundwater extraction volumes nearly equaled total water export from the valley at this time. Precipitation error bars show one standard deviation from the mean.

agricultural production decreased sharply. In Owens Valley today, ~4368 ha are routinely, but not consistently, irrigated for crops and pasture (Table 1).

Los Angeles's growing need for water led to the operation of a second, parallel aqueduct in 1970, which increased export capacity >60%. Since then, when surface water was insufficient to fill the aqueduct, groundwater was used. Groundwater pumping significantly lowered water tables in many areas of the valley. In particular, large changes in depth to water (DTW) were documented during the most recent drought of the late 1980s and early 1990s (City of Los Angeles and County of Inyo 1990b; ICWD, *data on file*). During this period groundwater resources represented a large fraction of total water exported (Fig. 3).

Only a few regions of Owens Valley remained relatively unaffected by intense human disturbance and hydrologic alterations over the past 100 yr. Two such regions are located north of Big Pine (Fig. 1) and east of Lone Pine. In our analysis, we consider vegetation change in these two regions to more closely reflect natural variations in ecosystem condition.

METHODS

Measurements of water resources

In Owens Valley, hundreds of monitoring wells exist to measure DTW. Because they were installed at different times and for different reasons, the monitoring wells are not systematically located, and they tend to be concentrated near LADWP pumping wells. From this group, we selected 171 shallow aquifer wells (piezometers) that were located in a wide range of plant communities and which had sufficient data during our study period. We used April DTW measurements because nearly all piezometers were read in April of each year (they are read intermittently at other times of the year). Highest water levels commonly occur during April before groundwater tables decrease due to natural processes (evapotranspiration) or extraction; thus these readings should annually provide the most consistent data on maximum groundwater resources available to phreatophytic plants throughout the year.

LADWP, ICWD, and the National Oceanic and Atmospheric Administration maintain 15 precipitation gauges within or near the study area. Six of these gauges possess records for the entire 1986–1998 study period. Data from the others were used for specific analyses.

Vegetation survey

Between 1984 and 1987 LADWP surveyed and produced a vegetation map of its Owens Valley land holdings (90 300 ha). Areas of apparently homogeneous vegetation were delineated on air photos, then field measurements were made in these parcels using the line point transect method (Heady et al. 1959, Bonham 1989). On average, five 33-m transects were run per parcel and percent cover by species was recorded (City of Los Angeles and County of Inyo 1990a). General plant communities mapped during this survey (described earlier) are summarized in Table 1 and Fig. 4B.

ICWD annually reinventoried up to 134 of the vegetation parcels in 1991–1998 to measure change since the original survey. Parcels for reinventory were selected to cover a range in proximity to well field areas and included several control parcels not believed to be affected by pumping. For ICWD/LADWP monitoring purposes, data on parcel hydrologic changes are typically estimated based on values recorded at the nearest piezometer and precipitation gauge locations (Manning 2001).

Remotely sensed data

Cloud-free Landsat Thematic Mapper data were acquired during September of each year, 1986–1998. Processing of these images followed Elmore et al. (2000). The data set was coregistered to within one pixel, calibrated to a common spectral response using temporally invariant surface features, georeferenced, and analyzed for %LC using spectral mixture analysis (SMA). In
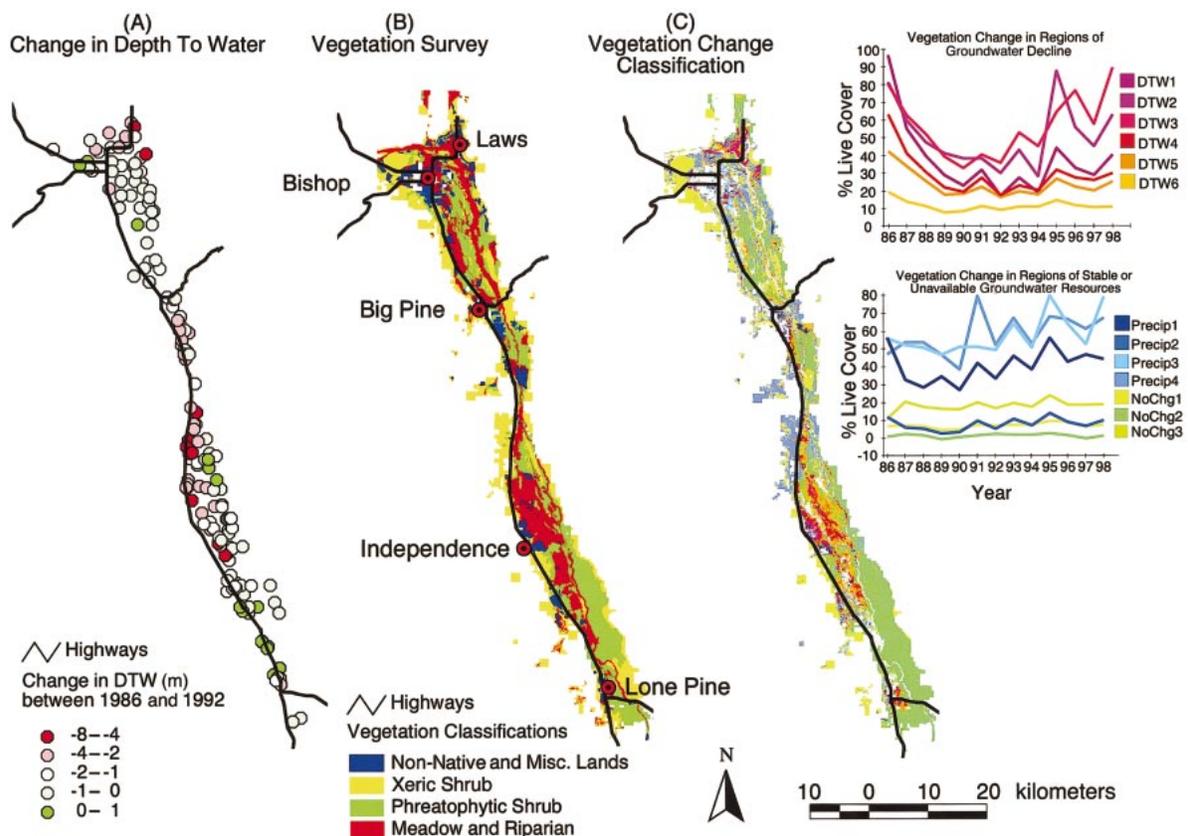
Fig. 4. Maps showing the spatial extents of (A) the change in depth to water recorded by 171 piezometers between 1986 and 1992; (B) the plant community distribution mapped by LADWP during a 1984–1987 inventory; and (C) the distribution of 13 vegetation response classes resulting from spectral mixture analysis (SMA) of Landsat TM data. Riparian communities, which represent a relatively small area at this scale, have been added to meadow communities in (B). The two graphs in the upper right show the 1986–1998 annual average percent live cover for each change class in (C). DTW, Precip, and NoChg designate change classes representing depth to water dependent changes, precipitation dependent changes, and static vegetation conditions, respectively (see *Results*: *Linking environmental drivers*).

SMA (Adams et al. 1986, Mustard and Pieters 1987, Smith et al. 1990) the spectral properties of a given pixel are modeled as a linear combination of the spectral properties of fundamental, basic materials found in the scene such as green vegetation and soil. These materials are referred to as endmembers. The proportion of each endmember required to model (through linear addition) the spectral properties of a pixel is a measure of the pixel area covered by that endmember. In Owens Valley, four endmembers representing light soil, dark soil, vegetation, and shade were found to best model the total variance within pixels. Through a comparison with data from 33 permanent vegetation monitoring sites representing phreatophytic shrub and meadow communities, SMA estimates were found to be accurate to within 4.0%LC. Furthermore, change in live cover was found to be accurate to within 3.8%LC (Elmore et al. 2000).

SMA processing resulted in a data set for the equivalent of one million 28.5 × 28.5 m plots, in which the %LC was measured every year for 13 yr. To simplify this voluminous information we used a clustering technique to classify the surface into land cover units that exhibited common response traits.

For the classification we developed parameters designed to capture the dynamic range of vegetation response. To account for net change, we calculated the change in %LC since 1986 for each year between 1987 and 1998 thereby normalizing the annual estimate to 1986. In addition, we calculated the change in %LC for each pair of consecutive years between 1986 and 1998. This parameter emphasizes the rate of change in %LC, which may be characteristic of plant community sensitivity to change. These calculations provided 24 variables. The mean pixel %LC was then added to the data set to potentially group pixels with similar total cover. This parameter might allow us to distinguish, for example, a stable low-cover xeric community from a stable, high cover meadow community. The standard deviation of the pixel's mean %LC was then added to the data set as a measure of variability. Finally, each pixel was assigned a value (between 1 and 29) based

on the plant community it had been assigned to during the LADWP vegetation survey (Table 1). Because we were also concerned that a single parameter (possibly larger in magnitude but not importance) might control the classification scheme and drive the results toward that response, we subtracted the parameter mean from each data point then divided by the standard deviation of that parameter. This process brought each of the 27 parameters, including the plant community parameter, to a common mean and variance and ensured that the classification algorithm would weight each parameter the same throughout the analysis.

Using an unsupervised classification algorithm called isodata (Tou and Gonzalez 1974) available in many remote sensing software packages we clustered the 27-parameter data set. The algorithm is designed to form clusters (classes) the means of which are evenly distributed in data space. Processing consisted of iteratively clustering the pixels using the minimum Euclidean distance technique and recalculating class means. We constrained the model to retrieve between 20 and 30 classes and the algorithm formed 23 classes after 10 iterations. The isodata-clustering algorithm has been found to be useful for generalizing data in many different disciplines and applications (e.g., Vanderzee and Ehrlich 1995, Host et al. 1996).

The resulting classification thus groups regions of the valley demonstrating a similar response pattern over the 13-yr period. Ten of the classes each covered only small areas of the valley and appeared to be associated with actively tilled fields or urban centers, or they resulted from remote sensing data errors. These classes, totaling 9324 ha or ~10% of the study area were removed from the analysis, thereby reducing the number of change classes to 13. The average %LC through time was calculated for each class.

The plant community assignment is one parameter that was not remotely derived, and also may not be available in other studies. To test the sensitivity of our classification to this parameter we performed isodata clustering procedures with the following variations: (1) the plant communities were assigned values ordered roughly according to water dependence (i.e., the order in Table 1); (2) the plant community parameter was removed; and (3 and 4) plant communities were assigned randomized values in two different runs. The isodata clustering procedure was applied to each of these data sets and an extensive analysis of the results was completed for (1). For the other three classifications, we compared the results against (1) to determine the stability of the result in terms of spatial pattern, coherence of each class, and the similarity of the various modes of response that were separated by the algorithm. Except where otherwise noted, references to the change classification refer specifically to result (1).

Change class analysis

The 13 change classes were characterized according to their plant community composition. By querying the change class results using GIS, we determined which LADWP-assigned plant communities dominated each of the change classes and, conversely, how the change classes were distributed among the plant communities. Examples of each change class were visited in the field and/or ICWD field data were consulted to analyze floristic components of change.

To analyze the various environmental drivers potentially responsible for each change class, we reviewed field reinventory data, characterized the expected response patterns to single drivers using a limited data set, then analyzed the entire data set for correlations with hydrologic data. To derive the expected vegetation response to change in DTW, we selected piezometers located in three major vegetation types: meadow (45 piezometers), phreatophytic scrub (46), and exotic (19). Using the 9 pixels (7300 m²) centered on each well, the average SMA %LC in 1986 and 1992 was calculated. The %LC difference was regressed against the difference in DTW between 1986 and 1992. To develop the expected vegetation response to precipitation, we used annual precipitation measurements from all 15 gauges for 1990–1996, a highly variable period (Fig. 3). The area within 10 km of each precipitation gauge was searched for parcels dominated by xeric or exotic annual species. For each gauge and year, the SMA %LC values for the 5–15 parcels of each type were averaged. We then performed linear regression on the annual differences in precipitation and %LC.

Based on results of the above exercise, data for the 13 change classes were evaluated with regard to the hydrologic drivers. To determine the relationship between change class response and precipitation, class annual average %LC values were regressed against the valley-wide average annual precipitation for the corresponding year between 1990 and 1996. To determine whether a change class was affected by declining water tables, the proximity of the change class to pumping wells and the pattern of %LC change between 1986 and 1990 was analyzed.

Finally, data on current and historical land use were consulted to assist in describing some changes that could not strictly be accounted for by hydrologic drivers. These data were derived from historical maps as well as recent field observations.

RESULTS

Phreatophytic plants and groundwater

There was a wide range in the temporal variability in DTW among Owens Valley piezometers. The areas showing the greatest water table decline, however, typically occurred in areas of greatest pumping: the areas north of Bishop and along the western side of the valley between Big Pine and Independence. During 1986–1992, 87 of the 171 piezometers recorded <1 m change in DTW despite six consecutive dry years (Fig. 4). Another 41 wells exhibited a decrease in the water table
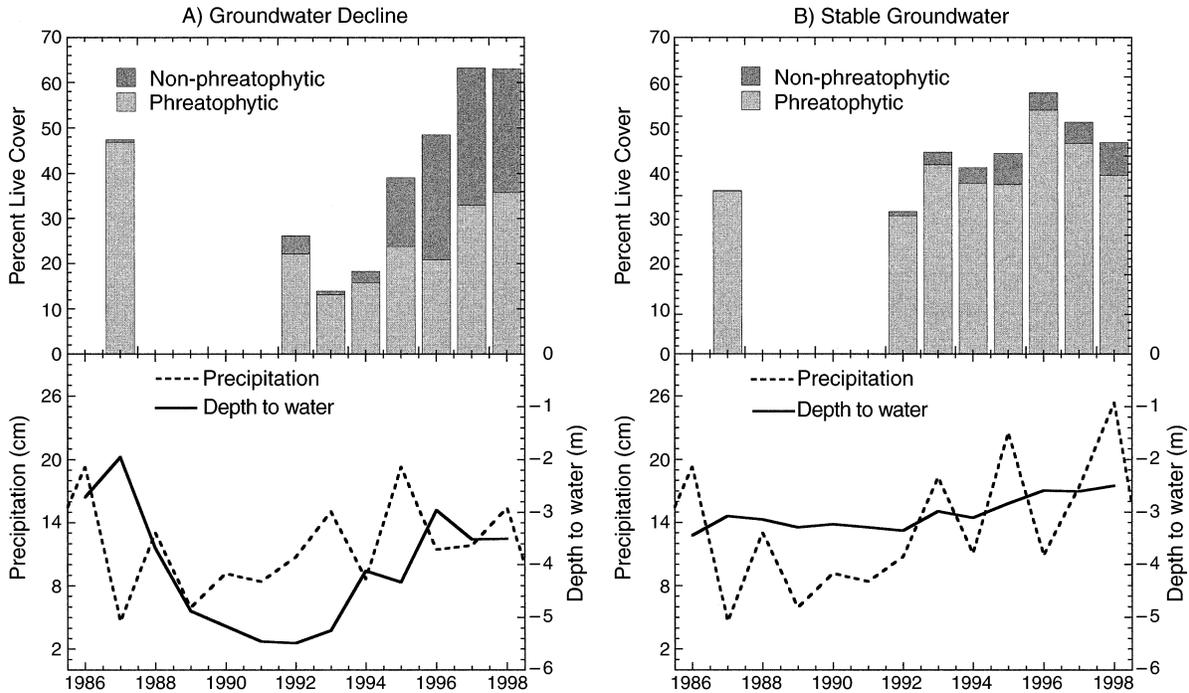
FIG. 5. Comparison of field-measured vegetation conditions, depth-to-groundwater, and annual precipitation in two meadow parcels monitored by Inyo County: (A) parcel LAW107, which exhibited a decline in water table, showed a decline in phreatophytic and an increase in nonphreatophytic (typically exotic annual) species; (B) parcel PLC121, which exhibited stable groundwater and vegetation conditions, including a constant relative proportion of phreatophytic and nonphreatophytic species.

from 1 to 2 m. Thirty-one wells recorded a groundwater decline from 2 to 4 m, while the remaining 12 wells recorded a decline >4 m. (Fig. 4)

In addition to pumping LADWP employs the practice of water spreading in years of above average snow pack. For example, during 1984–1986 abundant runoff from the Sierra Nevada was released onto vast areas north and east of Independence in an effort to prevent it from overloading the aqueduct. Some of this water seeped into the shallow aquifer, temporarily elevating the water table prior to the drought of the late 1980s. Although not a direct consequence of pumping, the effect of halting water spreading is the same: groundwater levels declined in these areas between 1986 and 1992, which was concurrent with a regional drought, and the decline was due to a change in water management practices.

Field data from two reinventoried parcels, one exhibiting a variable and the other exhibiting a constant water table, illustrate the range in cover and floristic changes. Data for a meadow community indicate that where the water level declined >3 m to below 5 m between 1987 and 1992 a 70% reduction in %LC occurred, primarily due to loss of phreatophytic grass cover (Fig. 5A). Increased rainfall and a rise in the water table between 1992 and 1998 were accompanied by an increase in %LC. Vegetation cover in 1998 exceeded %LC in 1987, but the life form composition

changed from mostly phreatophytic grasses and shrubs to a mixture of phreatophytic species and nonphreatophytic species. More than 90% of the increasing nonphreatophytic species were exotic annuals, mostly bassia.

A control meadow parcel, located between Bishop and Big Pine, exhibits a more or less constant pattern of both %LC and DTW (Fig. 5B). Water level, measured in a piezometer located on slightly higher ground near the parcel, was 3.5 m in 1986 and increased slightly through the drought. Relatively stable vegetation conditions were observed through this period, with the relative abundance of phreatophytic grasses and shrubs and nonphreatophytic plants remaining constant. Of the 134 reinventoried parcels, all were phreatophytic communities, and 80 experienced varying degrees of anthropogenically induced water table declines, which were associated with declines in %LC during the drought period. The 54 remaining parcels were control parcels not located near active pumping wells, and they exhibited minimal fluctuations in water table and %LC during the drought (Manning 2001).

Results of the analysis of meadow and scrub community %LC changes at specific piezometer locations showed a significant ($P < 0.05$) decline in %LC with a decline in water table (Fig. 6). Exotic plant communities (not graphed) did not show a significant correlation with change in DTW. These results demon-
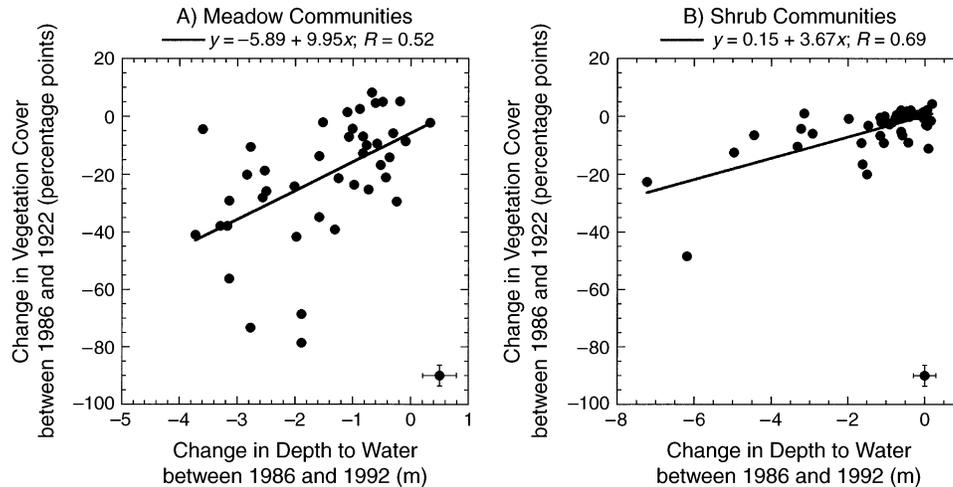
FIG. 6.   Comparison of 1986–1992 change in Landsat derived percent live cover estimates and change in depth to water table for (A) meadow communities and (B) shrub communities. Correlations were statistically significant for both community types ($P < 0.05$). Error estimates are presented in the lower right of each graph and were derived from the known uncertainty in estimating %LC using SMA (y-axis) (Elmore et al. 2000) and the uncertainty in assigning a depth to water measurement made during the month of April to the specific date of 1 April (x-axis) (A. Steinwand, *personal communication*).

strate that a decline in water table at least partially accounted for decreases observed in SMA-derived %LC between 1986 and 1992 in areas mapped as phreatophytic.

Xeric plants, Exotic annuals, and precipitation

From the early 1980s through 1998, the overall precipitation pattern was from wet to dry to wet (Fig. 3). Higher than normal precipitation during the strong El Niño years of 1983 and 1986 was followed by a drought period from 1987 through 1990. Precipitation was extremely variable from 1991 through 1996 with moderate rainfall in 1991 and 1996, high rainfall in 1993

and 1995, and dry conditions in 1992 and 1994. Finally, 1995 through 1998 were four consecutive years with average or above average precipitation.

Cover change in both xeric and exotic annual communities was strongly correlated ($P < 0.01$) with annual change in precipitation (Fig. 7). However, the total variation in %LC for xeric communities (Fig. 7A) is less than ±5%, a value very close to the uncertainty of our estimates of changes in %LC (±3.8%LC, Elmore et al. 2000). The relatively small variation in %LC with relatively large changes in annual precipitation is similar to the response observed in other studies of xeric vegetation (Went 1949, Beatley 1974). It also reflects
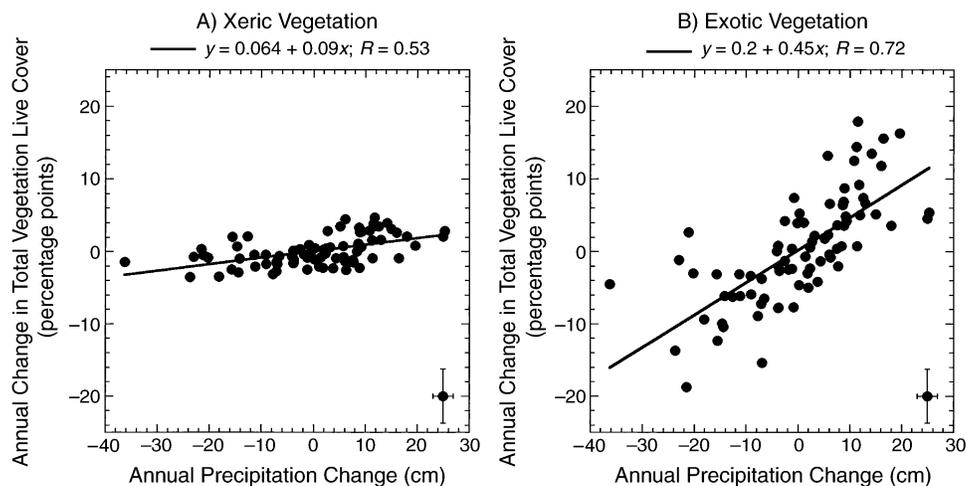

FIG. 7.   Comparison of Landsat derived annual change in percent live cover and annual change in precipitation for (A) xeric plant communities and (B) parcels dominated by exotic annuals for the years 1990–1996. Correlations were significant for both community types ($P < 0.01$); error estimates are presented in the lower right of each graph and were derived as in Fig. 6.

the sampling of vegetation %LC in late summer, well after early season annuals have senesced.

In contrast, we see a much greater change in %LC for a given annual change in precipitation for areas dominated by exotic annuals (Fig. 7b). The slope for exotic annual vegetation was much greater (0.45) than the slope for xeric vegetation (0.09). We conclude that exotic annuals demonstrate a response correlated with and, relative to xeric species, amplified with respect to precipitation. Field observations supported this finding: In wet years, high cover of bassia and Russian thistle can be found on sites that in dry years are barren. Based on these results, we expect that wildly fluctuating changes in SMA %LC may indicate an abundance of exotic annuals, especially if the changes correspond with wet and dry years.

Linking environmental drivers to change classes

The 13 change classes identified in the isodata clustering algorithm represent units of land cover that exhibit common change response and, to some extent, common community function over the 13-yr time period. Based on the relationships developed between %LC and water resources (DTW and precipitation), we analyzed and sorted the change classes within the context of these drivers. All but four classes exhibited a significant correlation with precipitation ($P < 0.05$).

Examination of the change classes revealed three that changed very little ($\leq 5\%$, close to the range of error in SMA %LC estimates) over the 13-yr period. These ''no change'' classes (labeled NoChg in Fig. 4) encompassed ~46 000 ha, or 51% of the study area and were composed of developed areas, water bodies, xeric scrub communities, and some phreatophytic communities (typically those located outside the influence of pumping wells) (Tables 2 and 3). No change 1 is dominated by alluvial fan xeric scrub communities that are drought tolerant and not dependent on groundwater resources. In the detailed analysis, cover in the xeric communities that dominate this class responded to precipitation (Fig. 7A), but the entire no change 1 was not significantly correlated with precipitation ($P = 0.058$). The class exhibited overall low cover and lack of a detectable trend through the 13-yr period (Figs. 4 and 8). The areas represented by no change 2 were generally distant from pumping wells, and the %LC response for this class was not correlated with precipitation ($P = 0.120$). From 1986 to 1998, this class included the most stable vegetation parcels in the valley, similar to PLC121 (Fig. 5B). No change 3 covered 2607 ha or <3% of the study area. Average cover in No change 3 was higher than in the other no change classes (Fig. 4) and was correlated with precipitation ($P = 0.008$), but annual cover change was small in magnitude.

Areas within the 10 remaining change classes (34 917 ha) exhibited changes in %LC larger than 5%. Unlike the no change classes, we found these change classes in areas of the valley that had been disturbed

(e.g., previously cultivated) or had experienced anthropogenic hydrologic alterations.

Piezometers in the regions north of Bishop and between Big Pine and Independence recorded declining water tables between 1986 and 1992 (Fig. 4A). This pattern is illustrated in the piezometer located in LAW107 (Fig. 5A), and the dependence of phreatophytic %LC on groundwater was demonstrated both in the ICWD vegetation data and our analysis of SMA %LC for areas of phreatophytic vegetation around piezometers (Fig. 6). In regions of groundwater extraction, the predominant change classes exhibited a response to groundwater decline characterized by a linear decrease in %LC between 1986 and 1990 (Fig. 8). Based on this pattern, we thus identified six change classes that exhibited a linear decrease in %LC from 1986 to 1990.

The six DTW change classes vary in their average cover over the 13-yr period and in their response following the drought (1995 and after) (Figs. 4 and 8). All the meadows and two phreatophytic scrub communities had the majority of their area within the DTW classes (Table 3). In contrast with the no change classes, however, there were no distinctive community composition differences within the DTW classes (Table 2).

Lands classified as DTW1 experienced a decline in %LC during the drought, followed by a small increase in %LC after the drought, which was correlated with precipitation. Field data and observations showed that the increase was primarily due to annual exotic species. Prior to 1995, the DTW2 response pattern was similar to DTW1, but in 1995, it exhibited a sharp %LC increase that was then followed by a decrease. Data and field observations revealed that a recently introduced exotic perennial species, perennial pepperweed (*Lepidium latifolium*), was partially responsible for the response pattern. LADWP subsequently initiated herbicide treatments. In some DTW2 areas, bassia increased in 1995 but was less abundant from 1996 to 1998. In regions classified as DTW3 cover increased following the drought, and data suggest the increase was due to higher cover of weeds and/or native species. LAW107 (Fig. 5a) was classified as DTW3 and DTW1 in approximately equal amounts.

DTW4, DTW5, and DTW6 often occurred in adjacent regions and in many cases included the same plant community types (Table 2). DTW4 was most prevalent in the water spreading area east and north of Independence (Fig. 4). In these regions, water tables were supported by spreading during the wet years of the early to mid-1980s, but declined with the cessation of spreading during the drought and had not returned to pre-drought levels by 1998. DTW4 and DTW5 also occurred in the central area of the valley halfway between Independence and Lone Pine, near Lone Pine, and in a location near the highway between Bishop and Big Pine. Some of these areas are leased by large ranching

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TABLE 2. Description of geographical extent and community composition of the 13 change classes.

Change class	Area (ha)	Description
No change 1	15 988	Occurs in proximity to precip2. Includes nearly all relatively undisturbed alluvial fan xeric scrub communities: creosote bush, blackbrush, Mojave mixed woody, and Great Basin mixed.
No change 2	27 464	Includes low cover valley floor parcels that did not demonstrably change. Dominated by greasewood, desert sink (a mixture of phreatophytic and nonphreatophytic species), and shadscale scrub (xeric). These areas tend to have exposed light-colored alkali soil.
No change 3	2607	Tends to occur in riparian areas and some alkali meadow, desert sink and greasewood communities, which are all phreatophytic. These sites probably had a relatively constant water supply throughout the study period.
Depth to water 1	888	Occurs in pumped areas, but relatively small in extent. Alkali meadow and agricultural lands, both with an abundance of weeds, dominate.
Depth to water 2	745	Frequently occurs adjacent to (and community composition similar to) DTW1, but response pattern includes a sharp cover increase in 1995 following the drought. The increase was primarily due to the exotic species *Bassia hyssopifolia* and *Lepidium latifolium*.
Depth to water 3	918	Commonly associated with DTW2. Dominated by meadow communities, particularly rush/sedge and nonnative meadow, that experienced increased cover of exotics, native species, or both following the drought.
Depth to water 4	2538	Prevalent in water spreading area east of Independence; also common in pumped areas. Three-quarters of class is meadow; remainder dominated by Nevada saltbush scrub and tamarisk scrub.
Depth to water 5	4297	Frequently occurs adjacent to (and community composition similar to) DTW4. May also be associated with changing pasture irrigation practices. This class included some tamarisk scrub parcels, dominated by *Tamarix ramosissima*, an exotic perennial species.
Depth to water 6	7764	Mostly associated with DTW5, but also scattered throughout valley. Includes approximately equal amounts of meadow and phreatophytic scrub communities. Many of these areas had low cover prior to the drought and even lower cover since the drought.
Precipitation 1	2050	Occurs in agricultural lands, both abandoned and currently irrigated, and some meadow areas. Evidence suggests these are areas where exotic annuals proliferate due to precipitation and increased water availability in irrigated areas in wet years.
Precipitation 2	13 571	Predominantly occurs where alluvial fans meet the valley floor. About one-third is Great Basin mixed scrub, one-third is rabbitbrush scrub or big sagebrush scrub, and most of the remainder is other scrub communities. Many of these areas were cultivated prior to 1930. *Salsola tragus* and late-season annual *Atriplex* species proliferate in wet years.
Precipitation 3	1505	Mostly associated with currently irrigated fields and meadows that receive increased water during wet years. Remainder scattered widely, with some occurring in riparian zones, where higher water flows may occur in wet years.
Precipitation 4	642	Relatively small extent. Occurs in actively cultivated fields that experienced changes in management, and about equally associated with parts of meadows receiving irrigation tailwater. To a lesser extent, associated with riparian areas known to be dominated by rushes and cattails.

operations, so ranchers may have altered irrigation patterns in these areas. ICWD field data showed that %LC declined in parcels classified as DTW4 and remained low following the drought. Average %LC for DTW4 was significantly correlated with precipitation between 1990 and 1996.

DTW6 was the largest DTW change class, covering 7764 ha (Table 2). This class characterized the response of many low-cover parcels in meadow and phreatophytic scrub communities. Meadow, Nevada saltbush scrub, and, to a lesser extent, desert sink, dominated this class, and three meadow and two phreatophytic scrub communities had most of their area within DTW6 (Table 3).

The four remaining change classes exhibited nonlinear change in %LC during 1986–1990 and were found outside regions of groundwater extraction. Because all four classes showed a significant correlation with precipitation, and because annual changes in average %LC exceeded 5%, we regarded these classes as showing an amplified response to precipitation (Fig. 7). Precipitation classes 1–4 covered 17 767 ha or nearly 20% of the study area (Table 2). Annual, exotic, and/or invasive species were prevalent in these four change classes.

More than 50% of the area within the following communities were characterized by the precipitation classes: "irrigated agriculture," abandoned agriculture, big sagebrush scrub, and rabbitbrush scrub (Table 3). Thirty-eight percent of the desert saltbush scrub area was also classified as amplified with respect to precipitation. The first two of these communities were obviously affected by past or ongoing cultivation. The latter three were known to be successional following past culti-

TABLE 3. Distribution of the plant communities among the three change-class types with percentage of the valley included in each group in parentheses.

Depth to water classes (19%)	Precipitation classes (20%)	No change classes (51%)	Split among classes
Nevada saltbush scrub (6)	irrigated agriculture (3)	urban (1)	desert saltbush scrub (precipitation 2)
Alkali meadow (6)	abandoned agriculture (2)	permanent lakes and reservoirs (1)	transmontane alkali marsh (no change 3)
Rush/sedge meadow (3)	big sagebrush scrub (2)		Modoc-Gr. Basin cot/wil riparian forest (precipitation 1)
Rabbitbrush meadow (6)	rabbitbrush scrub (2)	Mojave creosote bush scrub (1)	Mojave riparian forest (no change 3)
Nevada saltbush meadow (6)		Mojave mixed woody scrub (1)	Modoc-Gr. Basin riparian scrub (no change 3)
Nonnative meadow (3)		blackbrush scrub (1)	black locust woodland (no change 3)
Tamarisk scrub (6)		Great basin mixed scrub (1) shadscale scrub (2) desert sink (2) greasewood scrub (2) alkali seep (2) alkali playa (2)	

Notes: Communities listed under the three primary change-class groups had >50% of their area within those classes; the number of the class containing most of the area is shown in parentheses. Six community types were split among the groups, with at least some area in each group and <50% in any one group. Following the latter communities, the change class containing the greatest area is noted.

vation or disturbance. Although the classification algorithm distinguished irrigated agriculture from abandoned agriculture, it clustered the formerly cultivated parcels that had recovered some component of native
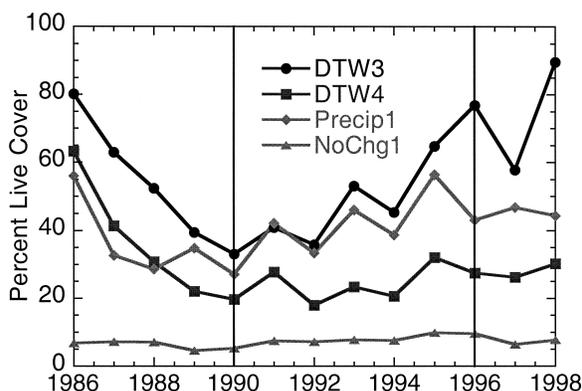

FIG. 8. Three primary modes of response were detected in Owens Valley over the 13-yr period: no change (NoChg), changes attributable to groundwater fluctuations (DTW), and changes amplified with respect to precipitation (Precip). Within these general categories, 13 classes were distinguished; examples of four are shown. For each of the three categories, unique features of the respective response pattern were used to separate individual change classes. For DTW, the linear decline in live cover between 1986 and 1992 was found to be distinct from that exhibited in the other change classes. After 1992, the Precip classes exhibited a response correlated with and amplified with respect to precipitation (Fig. 3). If a class exhibited a response characteristic of both DTW and Precip classes, it was assigned DTW; however a response amplified with respect to precipitation indicates the presence of exotic annuals in most cases.

shrub cover with many of the "barren" abandoned agriculture parcels (Table 2).

Three of the precipitation classes were characterized by relatively high average %LC throughout the study period, but the largest precipitation class, precipitation 2, exhibited low average %LC (Fig. 4). Precipitation 2 characterized the response of low-cover areas with relatively stable groundwater but in which summer annuals, especially the exotic Russian thistle, were abundant in wet years.

The change classification results described above were derived using the plant community parameter ordered by water dependence (Table 1), as one of the 27 parameters used in the isodata clustering procedure. When plant communities were assigned values at random or the plant community parameter was removed, the isodata procedure arrived at very similar results. In each case the same depth to water and precipitation classes were mapped and the spatial extent of each class was virtually identical; the only differences were minor changes in class assignment along class boundaries. Significant differences in class spatial extent were mapped across the large regions of xeric and low-cover phreatophytic vegetation unaffected by changes in groundwater or disturbance. These regions were dominated by the no change classes in all of the analyses and in each of the cases where the plant community parameter was included in the analysis, the xeric and phreatophytic plant communities were placed into separate classes, regardless of the order of the plant communities. When the plant community parameter was removed, the phreatophytic and xeric communities were clustered together into the same class, or these

communities were distributed among multiple no change classes. In this case the mean live cover parameter appeared to be the key discriminator of class membership.

DISCUSSION

The classification algorithm identified 13 classes that were subsequently determined to be different in composition and their response to environmental variables. As shown in Table 2, we found six classes associated with changes in DTW, four exhibiting amplified response to precipitation, and three exhibiting little or no change, and we showed community-level differences in response (Table 3). The success of the clustering algorithm was in part due to the large variability in vegetation response to the drivers of change. In addition, however, the 24 vegetation change parameters emphasized the dynamic properties of the surface and suppressed less informative properties such as total live cover. For example, normalizing the first 12 parameters to the predrought vegetation abundance of 1986 highlighted the relative effects of the subsequent drought and groundwater decline. Likewise, the annual-change-in-cover parameters (13–24) captured the highly variable nature of communities dominated by exotic annuals.

The plant community parameter, the only non-remotely sensed input parameter, proved most useful in distinguishing classes within the no change group that were not otherwise distinct in either average %LC or temporal dynamics. When the community parameter was removed from the isodata-input data set, xeric scrub (represented by no change 1) and low-cover phreatophytic communities (represented by no change 2) were joined into a single class. Despite similar average %LC, fan and valley floor communities differ significantly in species composition, phenology, and function. Therefore, the field survey information was useful for separating these two low-cover communities that exhibited a similar response, despite differences in ecology.

We attribute the stability of the no change classes to the relatively small amount of anthropogenic disturbance. No change 2 represented phreatophytic communities with a constant supply of groundwater available in sufficient abundance that precipitation did not greatly alter %LC of native species. No change 1 highlighted the drought resistant nature of the xeric communities. Areas within each of these no change classes could be selected as controls for more intensive field monitoring of floristic responses in the absence of disturbance and hydrologic alteration.

Another result with monitoring implications was the identification of DTW change classes in regions of groundwater pumping or changing irrigation practices. Close examination revealed a "bulls-eye" pattern, with a central intense response (DTW1 or DTW4) surrounded by concentric rings of less intense response (for

example, DTW2–DTW3–DTW6, or DTW5–DTW6). This information is clearly useful in field monitoring efforts designed to detect the regional extent and severity of vegetation changes associated with changes in water management practices. Through the identification of concentric patterns of change, the classification provides the context for field measurements of change and highlights where these changes were largest.

Field data and observations showed that, for parcels dominated by DTW1–3, the first response to abundant precipitation in 1995 was an increase in exotic weed species. The exotics died back in subsequent years in these three DTW classes, and DTW3 showed the most notable recovery of native phreatophytes by 1998. Once invasive exotic annuals establish, however, their control becomes increasingly difficult as they contribute to the seed bank and as repeated cycles of drought or water table manipulations create conditions conducive to their continued success at a site (Randall and Hoshovsky 2000). Piezometer measurements showed that for a considerable portion of the areas classified as DTW1–3 (e.g., Fig. 5A), water tables rose toward and sometimes matched predrought levels, but because of the abundance of exotics, future conditions in DTW1–3 areas are difficult to predict.

Exotic annuals were not as evident in DTW4–6 following the drought. In these areas, stress from declining water tables may not have reached the point where exotics could effectively compete with native perennials. But, an equally likely explanation may be that anthropogenic disturbance is relatively new in these areas and weed propagules have not arrived and flourished in high enough abundance to be detected with remote sensing. Another factor that may stifle weed success is that predrought hydrologic conditions were not restored throughout most of these areas by 1998. However, a potentially adverse decline of >50% from the 1986 level was detected in these three change classes during the drought, and %LC did not return to previous levels once precipitation patterns increased. All three classes showed a significant response to precipitation during 1990–1996. This suggests that by removing groundwater as the primary water supply, %LC of the remaining plants increased and decreased in response to precipitation. This pattern differs from the typical valley floor response pattern of communities not affected by pumping or water spreading, represented by no change 2, in which %LC was not correlated with precipitation and remained relatively constant.

Thus, altering the hydrology through such practices such as groundwater pumping and intermittent water spreading was shown to reduce %LC of native phreatophytic vegetation during a period of drought. This response was evident across 17 150 ha or 19% of the valley. One consequence identified was the proliferation of exotic annuals that may irreversibly alter the

species composition and thereby the ecological function of these phreatophytic communities. Research by others has identified similar or more complex floristic changes associated with groundwater decline (Mahoney and Rood 1992, Bernaldez et al. 1993), but these studies are typically focused on changes directly associated with stream hydrology. Studies identifying the relationships between indicator species and groundwater status across broader regions (Allen-Diaz 1991, Stromberg et al. 1996, Castelli et al. 2000) are invaluable for predicting where hydrologic alterations will have the largest effects. But these studies might fail to correctly predict changes in species distribution driven by changes in groundwater, particularly where groundwater decline is rapid and therefore faster than plant roots can extend into the capillary zone (Le Maitre et al. 1999). Our work extends this understanding by demonstrating that hydrologic alterations can alter land cover and community dynamics (e.g., reduced cover and proliferation of exotic annuals), and remote sensing can be effectively used to map and quantify the extent of change across vast regions.

Rabbitbrush scrub, which had been mapped as a phreatophytic community, was one of the communities prevalent in precipitation 2, which otherwise included communities dominated by nonphreatophytes. There are two explanations for this result. First, rabbitbrush scrub often occurred in areas not strongly affected by groundwater pumping. Therefore, without fluctuating groundwater as a driving influence, the variable pattern of partial exotic live cover driven by precipitation is the more obvious response. ICWD field data from rabbitbrush scrub parcels recorded, in wet years, up to 10% exotic annual cover, which is more than enough to drive a partial precipitation response in an otherwise phreatophytic plant community. Second, the dominant perennial plant found in these parcels is rabbitbrush. As postulated earlier, it is highly likely that the dominant subspecies of rabbitbrush on these sites is *C. n.* ssp. *hololeucus*, the nonphreatophytic subspecies. If this subspecies derives its water needs from precipitation, and it co-occurs with annual species on these formerly cultivated sites, it would be possible for the sites to show an amplified response to precipitation. This remotely sensed response could be used to further identify areas erroneously mapped as phreatophytic. Using field investigations to analyze this finding may assist the land managers by more accurately classifying the vegetation for management purposes.

A description of the distribution of exotic plants in Owens Valley is far from complete. The presence of some agricultural fields abandoned 80 yr ago but that today show no evidence of repopulation by natural Great Basin shrub communities indicates that these systems recover slowly and inconsistently from disturbance. Others have found similar evidence (Stylinski and Allen 1999), which support the idea that communities build floristic relationships with environmental parameters over 1000-yr periods (McAuliffe 1994). Additionally, initial conditions such as management practices or soil conditions and soil age may influence the long term fate of abandoned land (Coffin et al. 1996, Steiger and Webb 2001). Our data raise more questions as well. We found a significant portion of land area with an increased proportion of exotic annuals following the drought in otherwise phreatophytic plant communities. An extended analysis will reveal the fate of these systems; however, we suspect that at least some of them have been altered beyond an elastic recovery. If every successive disturbance or hydrologic alteration leads to a small fraction of the landscape being converted to exotic-dominated land, the eventual progression in light of continued human manipulation of environmental parameters is toward a general replacement of natural communities.

Conclusions

The degree to which current and future water management decisions incorporate knowledge from the scientific community depends on the ability of scientists to inform managers and the public of the potentially adverse consequences of poor management. Additionally, the scientific community must provide tools and techniques that can be easily implemented to monitor the ecological effects of particular water development policies. Modern researchers readily use new technologies for acquiring and interpreting data. With these data, models are developed to gain a better understanding of landscape level processes. Often, however, a weak link has been the transfer of the data, analytical techniques, and modeling results to those most directly involved with resource management (Naiman and Turner 2000, Pringle 2000).

In Owens Valley, we used remotely sensed data to quantify and describe the role of groundwater decline and climatic variability on %LC of semiarid vegetation. To our knowledge there exist no other studies of comparable temporal range (13 yr), temporal resolution (annual), and spatial scale (28.5-m sampling over the entire region). Our analyses of these remotely sensed data with field observations identified large regions of the landscape exhibiting a loss in live cover associated with lowering of water tables. For the most part, these regions were meadows and groundwater dependent shrub communities. Field data from these communities showed an increase in exotic %LC, and we hypothesize that exotic annuals gain a competitive advantage in phreatophytic plant communities when groundwater tables decline. This change in life form dominance represents a change in the function of the ecosystem from one buffered from drought by available groundwater to one sensitive to small variations in precipitation. In contrast, live cover and plant community function was sustained in regions of phreatophytic vegetation where the depth to water did not change despite a regional drought. Climate variability, as a part of climate

change, has been predicted to increase in the near future. The coupling of climate variability with plant communities more sensitive to changes in precipitation will lead to interesting consequences regarding the conservation of these natural ecosystems.

These results demonstrate the utility of multitemporal remotely sensed data for the identification of critical areas of concern and the interpolation between field analyses of plant community change. Field data, despite being indispensable for measuring the floristic component of change, do not allow for rapid sampling of vegetation conditions over large spatial scales. Remote sensing data can be analyzed on an annual basis across the entire management region thus providing an important tool for areas lacking sufficient field data.

Ecologists interested in the time varying nature of landscapes must make a physical measurement from multitemporal remote sensing data and then employ statistical techniques to group areas of common response (e.g., Yang and Prince 2000, Rogan et al. 2002). We chose SMA as our physical measurement because of its consistent precision and accuracy through time and relative insensitivity to measurement conditions (Elmore et al. 2000, Qi et al. 2000). Success in identifying and mapping landscape-scale response with remotely sensed data has been achieved using a variety of techniques (e.g., Jano et al. 1998, Munyati 2000). However we believe that a quantitative measurement of a surface property employed over a sufficient length of time and with sufficient frequency is important in capturing the dynamic nature of vegetation change. As shown in this study, this approach can be useful to infer regional plant community pattern and process. Studies reporting the application of clustering algorithms to identify land surfaces exhibiting common change history are underrepresented in the literature. Interestingly, researchers have used these techniques on data acquired throughout a single year (e.g., DeFries et al. 1997). Monopolizing on seasonal phenology, these studies seek to map land cover across large spatial areas without identifying changes in land cover through time or at high spatial resolution. Our study uses similar techniques, but for a different purpose and scale.

In the coming decades, naturally flowing waterways will become increasingly altered and the numbers of people living in water scarce regions of the world will continue to grow (United Nations Population Fund 2001). Landscapes likely to be affected will be large and the impacts difficult to perceive. Therefore, unless this process is accompanied by an increase in applicable ecosystem research using innovative new tools, the plants, fauna, and landscapes of Earth will become even further degraded. Researchers must apply the same technological ingenuity employed to extract water resources to the preservation of ecosystems through sustainable management. We believe the results and techniques presented in this paper define a rigorous methodology to quantify environmental change. The techniques are readily transferable and thus can be used to efficiently manage arid and semiarid ecosystems around the world.

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