EFFECT OF DEPTH TO WATER ON VEGETATION CHANGE IN THE OWENS VALLEY

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EXECUTIVE SUMMARY

There are obvious relationships that exist between depth to water and vegetation in the Owens Valley. Riparian woodlands and wetland communities exist along and near the river, meadows and mesic shrublands exist on the floodplain further away from the river, and dry shrublands exist on the upland slopes. This spatial relationship between vegetation and distance from the river, which is common along rivers throughout the western United States, implies a relationship between vegetation and depth to water. Depth to water is least along the river and this is where vegetation is most productive and the plant communities are dominated by species with high water requirements. Depth to water is greatest on the slopes and this is where the species have the lowest water requirements.

On a closer look, the relationship is not so simple. In the region between the river and the upland slopes, the vegetation is very diverse. The meadows and shrublands are mosaics of different species and the distribution patterns of these species are complex. Plant species are largely distributed across a landscape in relation to the distribution pattern of environmental factors. Depth to water is one of these environmental factors influencing the distribution of plants, but it is not the only factor. Other factors include soil texture, salinity, slope and aspect, microtopography, grazing, precipitation patterns, and historical settlement impacts. A basic tenet of ecology is that all factors potentially influence all others and seldom does a single environmental factor explain the distribution of vegetation and its productivity, especially on the small scale. Although depth to water is certainly an important factor influencing vegetation in the Owens Valley, it is not likely to be the only factor.

The purpose of this paper is to begin to understand the relationship between depth to water (DTW) and vegetation change in the Owens Valley. We know that there is a spatial relationship between DTW and the distribution of vegetation in the Owens Valley. So we might assume that there may be some type of relationship between change in DTW and change in vegetation. We also know that DTW is not the only factor causing change in the vegetation in the Owens Valley. This paper represents a first step in attempting to determine how much of the change in vegetation in the Owens Valley can be reasonably associated with change in DTW, using the currently available data from the Owens Valley. Three sources of information are used in this paper to address this issue: conceptual data based on the scientific literature, measured DTW and vegetation data collected at 30 permanent monitoring sites by the Los Angeles Department of Water and Power (LADWP) and the Inyo County Water Department (ICWD), and vegetation data and estimated DTW data provided by ICWD.

All plants require water, but not all species require the same amount. Water-use efficiency (WUE) is a measure of the amount of water a plant uses to produce one unit of plant tissue. Species that occur in the Owens Valley have a very wide range of WUE values, less than 200 for some species to over 1,500 for others. WUE is also influenced by environmental factors. As water becomes more abundant, WUE decreases for many species (i.e., they use more water to produce one unit of plant tissue). Other factors, especially soil fertility, also influence the water efficiency of plants. In numerous research studies, the supply of additional water has not resulted in an increase in productivity of many plant species, in part because of the influence of other environmental factors.

Intuitively to many people, a rising water table (smaller DTW value) should benefit plants and a declining water table (larger DTW value) should harm plants. In the real world, the relationship is not so simple. A rising water table can actually harm most species if too much of the rooting zone becomes saturated from the rising water. Under conditions of saturated (waterlogged) soil, roots of most species die because of

lack of oxygen. Under these conditions, the reduced amount of roots can result in less water being available to the plants and therefore productivity of the plants decreases. Conversely, a declining water table may benefit plants if it results in more absorption of water from the root system expanding into a previously saturated soil zone that is now drained, thereby providing both water and oxygen to the roots.

LADWP and ICWD collect both DTW and vegetation data at 30 permanent monitoring sites. These data have been collected since the late 1980s and provide the best available data set to investigate the relationship between change in DTW and change in vegetation in the Owens Valley. We investigated this relationship using both graphical and statistical methods (Sign Test and correlation analysis). The hypothesis we tested with these graphical and statistical methods was that there was an inverse relationship between change in DTW and change in vegetation. This means that as DTW increases (groundwater becomes deeper) vegetation cover should decrease and as DTW decreases (groundwater becomes shallower) vegetation cover should increase.

Graphing DTW against total perennial cover and cover of each of the five major species for all 30 permanent monitoring sites results in a total of 174 graphs. The hypothesis is supported by data for some of the species and some of the sites and is refuted by data from other sites. Discussion of this many graphs is beyond the scope of this paper. Instead, we present six graphs that support the hypothesis and six graphs that refute the hypothesis. These graphically illustrate the complexity of the relationship between change in DTW and change in vegetation and show that there is no simple direct relationship between these two variables.

We applied a Sign Test as one means to statistically test the relationship between change in DTW and change in vegetation cover. This test is used to determine the consistency of relationship between direction of change in each variable, using all possible years and all possible sites. There were a total of 1354 observations included in this test of the hypothesis. The results were that 49% of the observations supported the hypothesis and 51% refuted the hypothesis. This 49:51 distribution was what would be expected by chance. Therefore, this statistical test indicates that the data do not support the hypothesis that there is an inverse relationship between change in DTW and change in vegetation cover.

We also applied correlation analysis to these permanent monitoring site data. We conducted a total of 110 correlation analyses, one for total perennial cover at each of the 30 sites and one for each major species at each site where that species occurred. Of these 110 analyses, 35% were statistically significant (95% probability level) and 65% were not statistically significant. These results indicate that we can be 95% confident that most of the time (65%), there is no relationship between DTW and vegetation cover.

We also investigated this relationship when groundwater was nearer the surface (2 m and 4 m). This did not increase statistical significance by much. Averaged over the five species, 33% of the correlations were significant when all depths to water were used. When only those sites with average DTW of 4 m or less were used, significant correlations increased to only 40%. When only those sites with average DTW of 2 m or less were used, significant correlations increased to 50%. Most of the increase in significance came from two shrub species, Nevada saltbush and rabbitbrush.

Each of the three analyses (graphical, Sign Test, and correlation analysis) of the permanent monitoring data resulted in the same conclusion, there is no simple direct relationship between change in DTW and change in vegetation. This conclusion is consistent with data from the scientific literature and general ecological theory. Vegetation change is influenced by a variety of environmental factors, of which DTW is only one.

ICWD has sampled vegetation on a number of parcels in the Owens Valley since 1991. Data have been collected on 137 parcels, but not on all parcels in all years. We used data from the 31 parcels with the most complete data as a second data set to investigate the relationship between DTW and vegetation in the Owens Valley. Measured DTW data are not available for most of these parcels. ICWD estimates DTW on these parcels and we used these estimated DTW values in our analyses. We took a similar approach to the analysis of these data as we did with the permanent monitoring site data. We used both a graphical approach and a statistical (correlation analysis) approach.

As with the permanent monitoring site data, graphs are presented from parcels that support the hypothesis and parcels that refute the hypothesis. These graphical presentations illustrate the complexity of the relationship between DTW and vegetation change. In some cases, there is a reasonable fit between change in DTW and vegetation cover. In other cases, the relationship is opposite to what might be expected. We conducted a total of 389 correlation analyses on these data. Overall, the relationship between DTW and total perennial cover was statistically significant on 71% of the parcels. However, this relationship was weak, explaining less than 10% of the variation between DTW and vegetation cover.

The results of the analyses of the permanent monitoring site data and the ICWD vegetation monitoring data indicate that the relationship between change in DTW and change in vegetation is not simple. This is consistent with ecological theory and with the results of ecological research reported in the scientific literature. Vegetation change in the Owens Valley is affected by changes in DTW, but the characteristics of this response and the magnitude of the response varies from site to site. The hypothesis that there is a simple inverse relationship between change in DTW and change in vegetation is not supported by the available data that have been collected in the Owens Valley. These results do not imply that DTW has no effect on vegetation. It does have an effect. However, this effect is modified by other ecological factors. At some sites, the relationship between change in DTW and change in vegetation is simple and is the relationship that supports the hypothesis that as DTW increases, vegetation cover decreases. At other sites, and overall, this inverse relationship is not supported by the data. A combination of factors are the cause of vegetation change in the Owens Valley.

INTRODUCTION

Even a cursory view of the Owens Valley reveals certain obvious relationships between native vegetation and water. Along the river, where water is most abundant, the vegetation consists of riparian species such as cottonwoods and willows, with wet marsh communities and lush meadows. Away from the river, but still within the floodplain, there is a mosaic of meadows and various shrubland communities. The meadows are still productive, but not as productive as those immediately adjacent to the river. The shrublands consist of moderate to dense stands of a number of shrub species, some almost monocultures and some mixtures of up to a dozen species. As one moves up the lower portions of the slopes, farther away from the river, desert shrubs take over. Dense at first, they become smaller and less dense as one moves up the slopes.

It does not take much imagination to picture in the mind's eye the correlation between that vegetation gradient and depth to water beneath the surface. Along the river, water is at or very near the surface. There is the lush vegetation. Away from the river, but still on the valley floor, groundwater must not be too far below the surface. This is the area of the meadows and the denser shrub communities. Then as one goes up the slopes, depth to water increases and the vegetation decreases correspondingly.

This is the pattern in the Owens Valley. It is also the pattern in other riparian areas throughout the desert region of the western United States. The lush vegetation along the river could not exist without the water the river and the groundwater system linked to the river provide. Without that extra water, the native vegetation throughout all of the Owens Valley would be similar to that on the slopes.

That is the obvious conclusion from the cursory view, the coarse scale, the broad look, the big-picture. At this level, the conclusion is correct. However, when we take a closer look, especially in the middle zone, we find that the picture is much richer and much more complex. Describing this middle zone as a mosaic of meadow and shrubland is too broad of a generalization. It does not do justice to the richness of the vegetation. When we look more closely, there are many variations of the meadows. Some are almost solid stands of saltgrass, looking almost like a mowed lawn. Others are stands of the bunchgrass sacaton, some clumps almost looking like hummocked dunelands. And there are numerous combinations of the two species, along with many other grass species.

The shrublands come in many more combinations than the meadows. There are majestic stands of big sagebrush, the indicator species of the Great Basin region of the western United States, with nearby stands of the same species only half the size of the big ones. There are near monocultures of Nevada saltbush, some stands so thick they are almost impossible to crawl through. There are greasewood flats and rabbitbrush meadows, stands of shadscale and ridges supporting horsebrush. And breaking the skyline, there are scattered cottonwoods, those along the river, creeks, and ditches, and those isolated few that indicate the location of an old homestead.

Why the diversity? Why so many plant communities, so many combinations of plant species? Certainly depth to water is one factor, a major factor. But is it the only factor? If not, what are the others and how important are they? Upon a closer look, other factors become apparent. The landscape is not flat, even on the valley bottom. There are areas slightly higher and areas slightly lower. The lower areas collect more runoff when it rains than those higher areas. The soils are not all the same. Some are sandy, some have more clay. Some have a lot of rock on the surface, many do not. Some areas stand white in the sun, salts at the surface, but fifty feet away there is no evidence of salts. There are herds of cattle, of horses and mules, and of elk. Look closely and you can see areas heavily used by rabbits, their pellets everywhere on the ground, and areas where the leaves of the shrubs have been consumed by insects. The history of the Valley can be seen written across the landscape – evidence of past fires, homesteads, fields, orchards, and roads.

Vegetation is dynamic – it changes constantly. Try as we might to keep things as they were, changes occur. Stands of saltgrass spread and contract. Sacaton plants grow, form clumps, and eventually die, to be replaced by others. Shrub seedlings establish, grow, and then may merge into thickets. There are wet years and dry years and the vegetation responds to both. Groundwater rises and falls, both because of pumping and because of changes in runoff. Vegetation responds to these changes also.

A basic tenet of ecology is that all things in an ecosystem are connected, i.e., all factors potentially influence all others (Daubenmire 1968:7, Billings 1970:4, Odum 1971:8, Whittaker 1975:2). A change in one factor will affect others. The effect may be large or small, but the system is interconnected. A primary challenge in ecology is how to study this complex system. A common approach is to concentrate on a small number of factors, perhaps only one, and try and understand how they affect the system. The advantage of this approach, often referred to as the "reductionist" approach (Smith 1992:6), is that it is manageable, it is "do-able". The danger in this approach is that we may ignore the affects of other factors and how they might influence our conclusions. But if we are careful, the reductionist approach can lead to valuable insights into how our ecosystems work. Then we can study additional factors and begin to build a more complete understanding of the ecology of our system.

The purpose of this paper is to begin this process by investigating the relationship between two factors, depth to water (DTW) and vegetation change, in the Owens Valley. Specifically, we will address the issue of whether or not changes in DTW are associated with changes in vegetation. We know that there is a relationship between DTW and the distribution of vegetation in the Owens Valley. So we might assume that there may be some type of relationship between changes in DTW and changes in vegetation. We also know that DTW is not the only factor causing change in the vegetation in the Owens Valley. Therefore, our first step, the step presented in this paper, is to attempt to determine how much of the change in vegetation in the Owens Valley can be reasonably associated with change in DTW, using the currently available data from the Owens Valley.

This paper is divided into five parts, the first part being this introduction. The second part presents general background information and concepts pertinent to the issue. The third part addresses the issue by reviewing data collected by the Los Angeles Department of Water and Power (LADWP) and the Inyo County Water Department (ICWD) at 30 permanent monitoring sites. Results of both graphical and statistical analyses are presented. The fourth part addresses the issue by reviewing data collected by ICWD as part of their annual vegetation monitoring program. Again, results of both graphical and statistical analyses are presented. The last part of this paper presents some conclusions based on our review of these data.

SECTION 1. CONCEPTS

Basic Concepts

All plants require water. However, different species of plants, and therefore different types of vegetation, vary considerably in their water requirements. These water requirements can also vary considerably for a given species, depending on environmental conditions.

Some types of vegetation require relatively large amounts of water to either survive or to dominate a site. Examples include woody riparian species such as cottonwood and willow, and marsh species such as cattails, rushes, and bulrushes. Plants adapted to wet environments are called hydrophytes (meaning water loving)(Daubenmire 1967:138; Smith 1992:544). The habitats these species occupy are often referred to as hydric, or wet, sites (Whittaker 1975:158). Some of these species, true hydrophytes, require abundant water to survive. Others can tolerate less wet sites, but do best under wet conditions.

Other types of vegetation can survive on, and dominate, dry sites. Examples in the Owens Valley include big sagebrush, rabbitbrush, and bursage. Species especially adapted to dry sites are called xerophytes (meaning dry loving)(Daubenmire 1967:142; Billings 1970:22). Other types of vegetation can tolerate somewhat dry sites, but become more abundant as moisture increases, at least up to a point (Dansereau 1957:139). Examples in the Owens Valley include sacaton meadows and greasewood shrublands. Species adapted to these intermediate sites are often called mesophytes (Daubenmire 1967:155). True mesophytes are those species that cannot inhabit very wet sites or very dry sites because most mesophytes lack the specialized physiological structures characteristic of either hydrophytes or xerophytes. The response of these three types of plants (hydrophytes, mesophytes, and xerophytes) to changes in depth to water can be very different (Bagstad et al. 2005).

Plants use water for various purposes. Different species may also use different amounts of water for the same physiological purpose. Water-use efficiency is one method of rating species by how much water they use. A common use of water-use efficiency is to determine how much biomass various species can produce from a given amount of water. The more efficient a species is (i.e., the less water required to produce a unit of plant biomass), the more ecological advantage it might have under conditions of limited water. Published data indicate a wide-range in water-use efficiencies for various plants (Table 1).

Table 1. Examples of published water-use efficiency (WUE = units of water required to produce one unit of dry biomass) values for various plant species.

Plant	Growth-form	Habitat	WUE	Reference
sumpweed	forb	Hydric	534	Shantz and Piemeisel 1927
dandelion	forb	Mesic	2855	Humphrey 1962:90
California poppy	forb	Xeric	897	McGinnis and Arnold 1939
Russian thistle	forb	Xeric	222	Dwyer et al. 1972
needlerush	grass-like	Hydric	785	Giurgevich and Dunn 1978
slender wheatgrass	grass	Hydric	885	Fairbourn 1982
bermudagrass	grass	Mesic	307	Biran et al. 1981
inland saltgrass	grass	Mesic	588	El-Haddad and Noaman 2001
cheatgrass	grass	Xeric	303	Link et al. 1995
black grama	grass		476	McGinnis and Arnold 1939
bursage	shrub	Xeric	232	Bamberg et al. 1973
shadscale	shrub	Xeric	570	Caldwell et al. 1977
rabbitbrush	shrub	Xeric	597	Donovan and Ehleringer 1994
greasewood	shrub	Xeric	840	Trent et al. 1997
big sagebrush	shrub	Xeric	1557	Downs and Black 1999
saltcedar	tree	Hydric	526	Glenn et al. 1998
willow	tree	Hydric	540	Glenn et al. 1998
cottonwood	tree	hydric	904	Anderson 1982
mesquite	tree	mesic	1432	Dwyer and DeGarmo 1970

In addition to differences in water-use efficiency among different species, there are differences within the same species when grown under different levels of environmental factors (Humphrey 1962:89). For example, Russian thistle (tumbleweed) has a high water-use efficiency (Table 1). However, it becomes more efficient as the amount of available water decreases and less efficient as the amount of water increases (Dwyer and Wolde-Yohannis 1972). When soil water is abundant (field capacity), Russian thistle has a water-use efficiency of 222. When soil water is low (10% of field capacity), it has a water-use efficiency of 98. Therefore, under moist conditions, Russian thistle uses over twice as much water to produce one unit of biomass than it does under dry conditions. Alkali sacaton, one of the two most abundant perennial grasses in the Owens Valley, provides another example. When grown at 5% soil moisture, sacaton is 24% more efficient in using water than when grown at 12% soil moisture (Montana et al. 1988). Water-use efficiency in a number of montane tree and shrub species in the western United States can triple, depending on elevation (Marshall and Zhang 1994). These three examples, along with others in the scientific literature (e.g., Nobel 1991:462), illustrate the fact that many plants use more water to produce the same amount of biomass when water is abundant and less water to produce the same amount of biomass when water is less abundant, or that their water-use efficiency is affected by local environmental conditions. This should be kept in mind when attempting to manage water supply to vegetation. One practical example is that increasing or decreasing water supply by some percentage is not likely to result in an equal change in plant response (i.e., the relationship between water supply and plant production is not linear; Kramer 1969:376). For example, increasing water supply by 10% will likely result in less than a 10% increase in plant production and a 10% decrease in water supply will likely result in less than a 10% decrease in plant response.

Numerous attempts have been made to correlate plant growth to available water. Intuitively, there should be a simple relationship between the two – add more water and the plants should grow more. However, this is often not the case. In these instances, the addition of water does not benefit the plant. An example is big sagebrush, the most abundant shrub species throughout the Great Basin region and one of the most abundant shrubs in the Owens Valley. In a field experiment conducted on established plants at a site receiving less than 6 inches of precipitation a year, supplemental water (5 inches) did not result in increased vegetative growth in the shrubs, although the watered plants did produce more reproductive structures (Evans and Black 1993). Although the watered shrubs did not produce any more vegetative growth, they did use more water than the unwatered shrubs, resulting in a lower water-use efficiency for the plants receiving the additional water. A study that added water to a native plant community in the Chihuahuan Desert also resulted in little response from the desert plants to the supplemental water (McLendon et al. 2001). A primary conclusion that can be drawn from these two studies is that more water does not necessarily mean more growth.

Another important aspect to consider when attempting to understand the response of plants to changes in resource supply, including water, is the ecological concept of limiting factors. Plant growth is a function of a number of factors, including resource supply. Plant growth requires a number of resources, such as water, nutrients, sunlight, and carbon dioxide. If the supply of any one of these critical resources drops to below the level required by the plant, growth either slows or stops, regardless of how abundant the other resources are. This concept is known as the law of limiting factors (Salisbury and Ross 1969:679). The resource in most limited supply, in relation to the requirements of the plant, controls the growth of the plant at that point in time. Under these conditions of limited growth, the supply of another resource may increase. The plant may continue to use this surplus resource at higher amounts, while not producing any more growth.

This concept can be illustrated with experimental data on the effects of water and nutrients on plant growth. Higher rates of nitrogen (N) fertilization (200 lbs N per acre vs. 50 lbs N per acre) tripled the water-use efficiency of coastal bermudagrass in a wet year and more than doubled it in a dry year (Figure 1; Burton et al. 1957). Similarly, at lower phosphorus (P) levels, alfalfa used over a third more water to produce the same amount of biomass than it did when P was more abundant (Figure 2; Viets 1962).

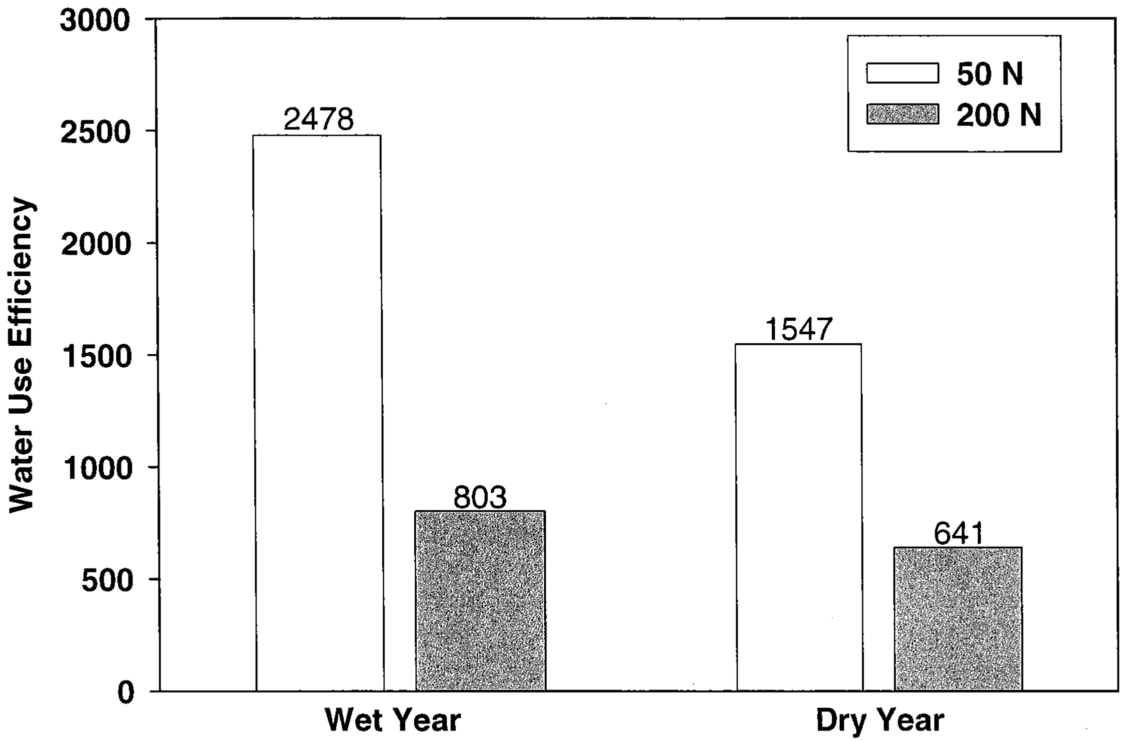

Figure 1. Effect of nitrogen (N; pounds of fertilizer per acre) on water-use efficiency of bermudagrass (data from Burton et al. 1957).

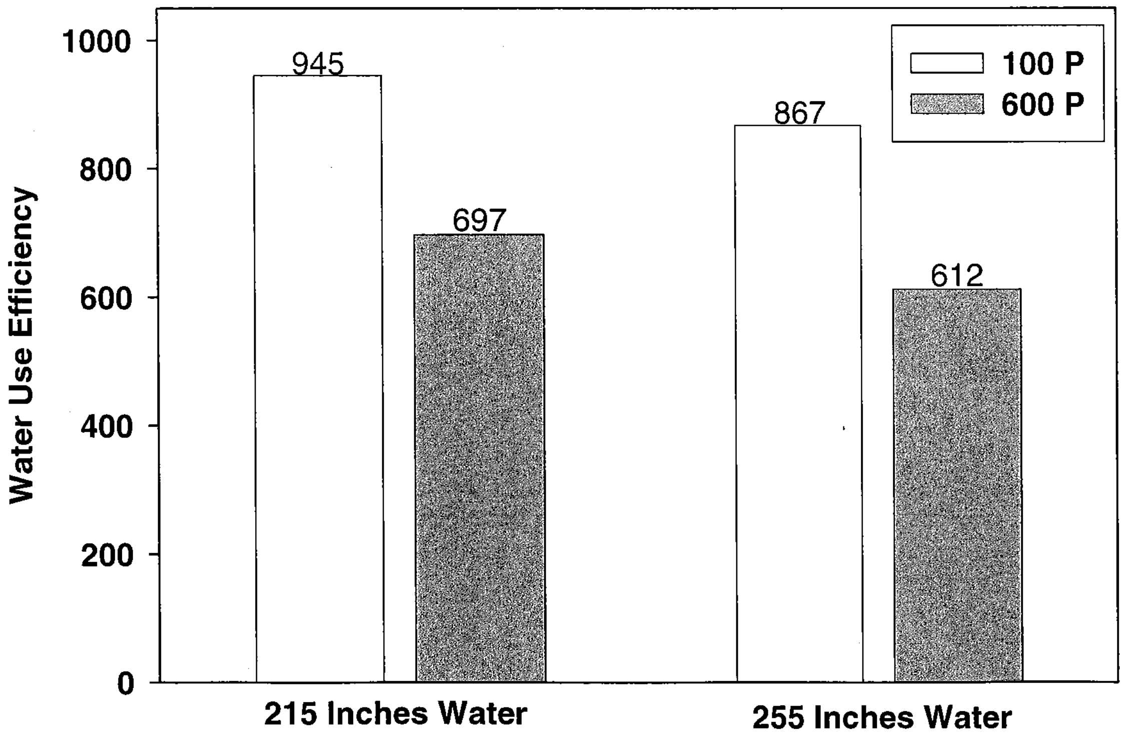

Figure 2. Effect of phosphorus (P; pounds of fertilizer per acre) on water-use efficiency (WUE) of alfalfa under two levels of irrigation (data from Viets 1962).

An important application of this concept in understanding vegetation dynamics in water-limited ecosystems is that more water is used by plants to produce the same amount of biomass under conditions of low nutrients than the same plants would use if nutrient levels were higher (Kormondy 1996:23). This relationship between soil nutrient levels and water-use efficiency has been found to be of importance in the ecological responses of desert shrubs in the eastern Sierra and western Great Basin regions. These shrubs have an inverse relationship between water-use efficiency and nitrogen-use efficiency, which may be related to their ability to succeed on the relatively low-nitrogen soils of the region (DeLucia and Schlesinger 1991). If so, greater availability of water to these plants will have a much more limited beneficial effect on their growth than would be expected if nitrogen was not a limiting factor. Stated another way, these plants may be relatively inefficient users of water in order to secure adequate amounts of nitrogen.

Effect of Water Table on Plants

Intuitively, to many people, a rising water table should benefit plants and a declining water table should harm plants. In the real world, the relationship is not so simple. Like many other ecological responses, change in depth to water can have both expected and unexpected effects on plants (Martin and Chambers 2002, Naumburg et al. 2005). This is especially true for species adapted to arid environments but that are growing in areas where abundant water may be present within their rooting zones – areas like the Owens Valley.

Assume that a plant is growing on a site where the groundwater is located near, but below, the lower rooting zone of the plant (Figure 3A). The plant can be either a grass or a shrub. For the purpose of illustration, we will assume that it is a shrub. Under this condition, the plant receives some supplemental water from the capillary fringe just above the upper zone of the groundwater. The amount of water the plant can receive from this capillary zone is dependent on 1) how high the water can be lifted upward by capillarity and 2) how many roots (more accurately, how much root surface area) are in contact with the moist zone. The height of the capillary rise is largely determined by the texture of the soil (Kohnke 1968:32).

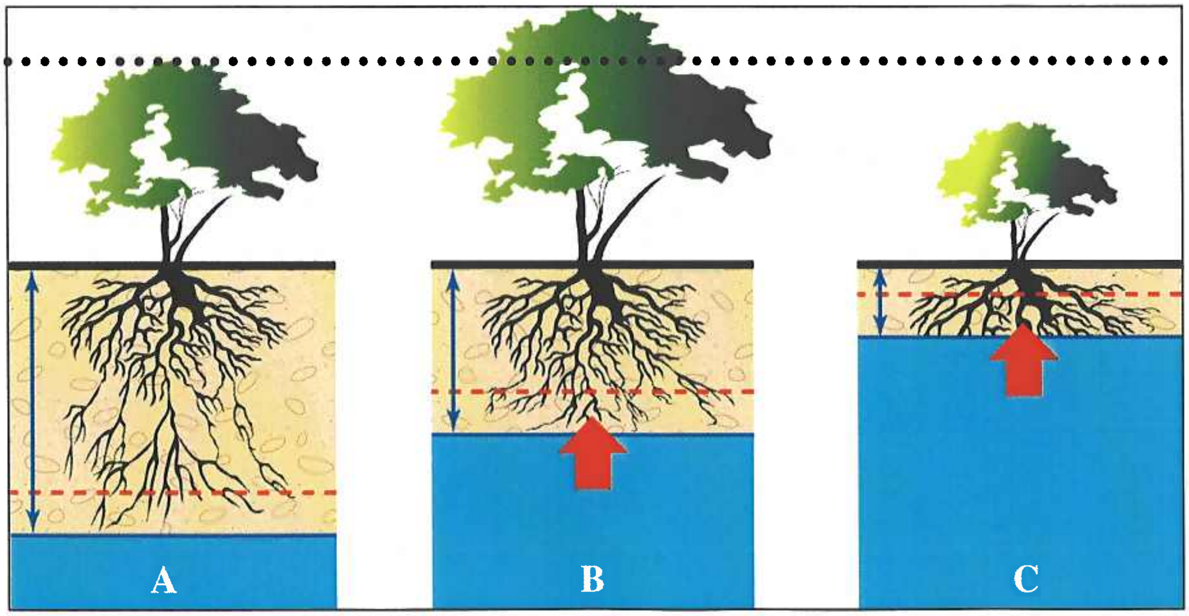

Figure 3. Conceptual model of the effect of a rising water table on plants.

Now assume that the groundwater rises somewhat (Figure 3B). Three ecological responses pertinent to this discussion occur. First, the soil corresponding to the height of the rise becomes saturated. Mineral soils are composed primarily of three components: minerals, air, and water (Foth and Turk 1972:2). The minerals (the soil particles) compose a matrix, with openings between the particles. These openings are called "pores" or "pore space". The size of the openings depend on the characteristics of the mineral particles (e.g., how many sand, silt, or clay particles there are), other solid materials present (such as organic matter), and how compacted the soil is. In unsaturated soils, the pore spaces are filled with air, with films of water around the particles (Foth and Turk 1972:65). As the soil dries out, the space occupied by the water is replaced by air. As the soil wets, e.g., following a rain, some of the air is replaced by water. Under saturated conditions, almost all of the air is replaced by water.

Roots require oxygen. They require oxygen for the same reason we do, to respire (Oosting 1956:193). If roots do not receive sufficient oxygen, they will die. Roots of most plants (we will discuss the exceptions shortly) cannot tolerate saturated conditions for very long because they will die from lack of oxygen, i.e., they will drown. So the second thing that happens in our illustration (Figure 3B), is that those roots in the saturated zone of the soil profile die.

The third ecological response is that the plant will probably increase in growth. This is because the amount of roots now in contact with moist soil along the fringe of the groundwater is greater than the amount of roots that died. Therefore, there is a net gain for the plant. It is receiving more water than it did before, even though it lost some of its roots.

Now assume that the groundwater continues to rise (Figure 3C). The higher it rises, the more soil becomes saturated and the more roots die (Weaver and Clements 1938:300). For a while, the plant still benefits because even more roots come in contact with water than die. But eventually, the water rises high enough that too many roots drown. At this point, the plant begins to suffer from a decreasing water supply because it has lost too many roots and the unsaturated zone, the only area it can extract water from, is becoming too small to support enough roots to supply the necessary water to the plant.

During the first two phases (Figures 3A and 3B), the plant benefits from the rising water table. During the third phase (Figure 3C), the rising water level is detrimental to the plant. The magnitude of both the beneficial and the detrimental effects depends on how much of the root system is affected by the rise in water table and what species are involved.

The reverse pattern occurs as depth to groundwater increases (water table declines). If the water table is high enough to be detrimental to the plant (Figure 4A), the plant is benefited by a decline in the water table. As the water table decreases, two important factors occur. First, the soil "drains", i.e., it shifts from a saturated to an unsaturated condition. As water drains out of the pore spaces, the volume previously occupied by water becomes occupied with air. This allows for the second factor to occur, roots grow into these zones (Martin and Chambers 2002). The roots are now able to extract the water that remains in the pore spaces and this water becomes available to the plant, whereas very little of this water was available to the plant under saturated conditions. The more the water table drops, the more the soil profile becomes unsaturated, and the more the roots can grow into this region and supply the plant with water (Figure 4B). The resulting beneficial effect to the plant continues as long as sufficient additional water is available in these newly unsaturated zones (Naumburg et al. 2005). Eventually, if DTW continues to increase, the effective rooting zone of the plant is reached (Figure 4C). At that point, a continued increase in DTW becomes detrimental to the plant, unless other sources of soil water (e.g., precipitation or surface runoff) are available to the plant (Scott et al. 2000, Bagstad 2005).

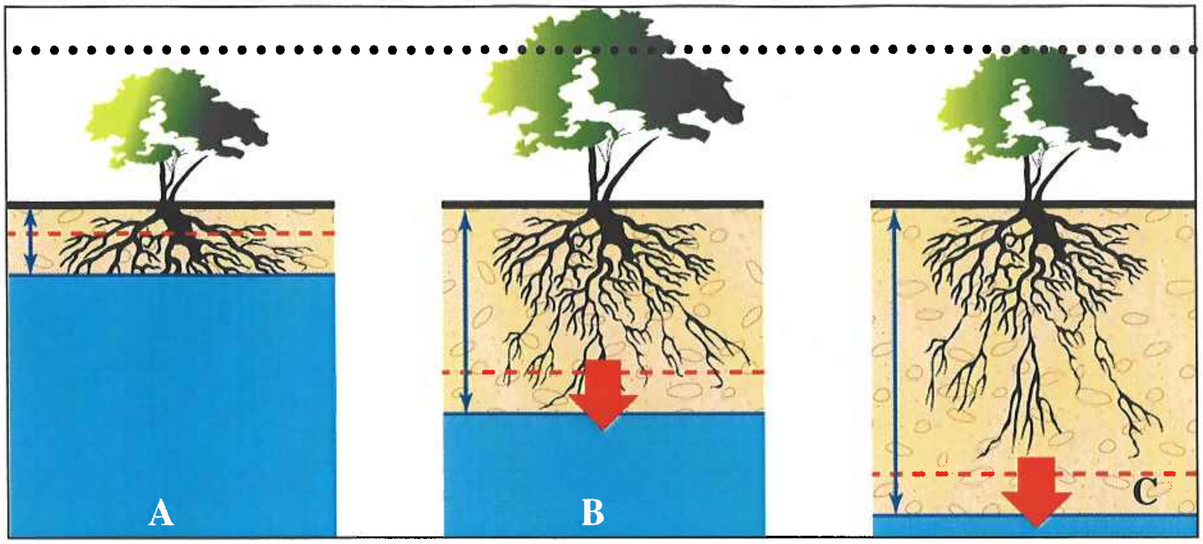

Figure 4. Conceptual model of the effect of a declining water table on plants.

As with the case of a rising water table, the magnitude of both the beneficial effects and the detrimental effects of a declining water table vary from site to site and from year to year. The ecological importance of these fluctuations depends on a complex set of factors including how far the water table declines, how fast the water table declines, ecophysiological characteristics of the plants, associated environmental factors (e.g., precipitation levels, temperatures), and other ecological factors (e.g., composition of the plant community, soil type, degree of livestock grazing)(Naumburg et al. 2005).

Plant ecology has long recognized the importance of competition among various types and species of plants in determining what type of vegetation successfully occupies a particular site (Weaver and Clements 1938:148). In many plant communities, competition is a major factor determining what species will succeed on that site. But in some types of ecosystems, tolerance to the effects of the environmental conditions may be just as important, and in some cases perhaps even more important than competitive ability. Extremely dry, saline, or cold sites quickly come to mind. However, sites with saturated soils are also an example of where tolerance is a very important ecological factor.

As mentioned previously, a characteristic of saturated soils is that these soils are anaerobic (have low oxygen levels) and roots require oxygen for respiration. Saturated soils are anaerobic. Anaerobic means lack of air. The roots of most species can tolerate anaerobic conditions for short periods of time, but not for sustained periods. The period that various species can tolerate saturated conditions varies, but for most actively-growing mesophytes and xerophytes it is a matter of days or weeks (Kramer 1969:139). Dormant plants can generally tolerate saturated conditions longer than when they are active.

Plant species adapted to wet sites, true wetland species, have roots that can tolerate the anaerobic conditions characteristic of saturated soils. These adaptations are of various types, but a common one is the presence of aerenchyma tissue (Keddy 2000, Cronk and Fennessy 2001). Aerenchyma are specialized porous tissues that allow a more rapid transport of oxygen from aboveground tissues to roots. Aerenchyma tissues are common in wetland species, but rare in upland species. Aerenchyma tissues have been reported in the roots of some xeric and mesophytic shrubs in the Owens Valley (Groeneveld and Crowley 1988). However, the presence of these tissues did not necessarily confer flooding tolerance to all of the species that had them. More commonly, upland species respond to saturated soils by producing shallower and more laterally extensive root systems (Weaver and Clements 1938:301; Oosting 1956:193; Groeneveld and Crowley 1988; Martin and Chambers 2001, 2002).

These differences in tolerance to saturated conditions and the associated aspects of competitive advantage become important as we attempt to understand what happens to vegetation when depth to water changes. A site with a very high water table is likely to support vegetation adapted to saturated soils. This vegetation dominates the site because it can tolerate the saturated conditions, not because it can directly out-compete the mesophytic or xeric species in such areas as growth rate, shading, or nutrient-use efficiency. If the water table decreases, wetland species are likely to be able to tolerate the conditions of the deeper water table at least for a time, especially if the decrease in water table occurs during the dormant season (a common occurrence with cattails) or remains within the rooting depth of the species. However, the deeper the unsaturated portion of the soil profile becomes, the more likely it is that more competitive species, such as mesophytic grasses and shrubs, will invade the site. Total perennial cover might remain high, because there is sufficient water for high productivity of grasses and shrubs, but species composition will change. Therefore, vegetation cover might decrease at first, as the wetland species become less productive, but then cover might increase as the grasses and shrubs become established. Therefore an increase in DTW (decrease in the water table) might first result in a decrease in cover and then an increase in cover, giving conflicting results unless species composition was taken into account.

Similarly, a site with a moderately-high water table might be dominated by mesophytic grasses, such as sacaton and saltgrass. This is typical of the alkali meadows in the Owens Valley. If DTW increased, but the water table remained well within the rooting zone of the grasses, there might not be much of an effect on vegetation cover. But as DTW continued to increase, there might be a decrease in grass cover but an increase in cover of the deeper-rooted shrubs. Total perennial cover might remain the same, or even increase, as DTW increased. Conversely, if DTW decreased, cover might also decrease because of loss of part of the root system of both the grasses and the shrubs. If DTW continued to decrease, wetland species might establish on the site but there would probably be a lag-period during which cover values would decrease. In this case, a higher water table would decrease vegetation cover, at least for some period of time.

These hypothetical examples illustrate the conceptual basis for why attempting to understand the relationship between change in DTW and change in vegetation may be challenging. Having presented this conceptual framework, we will now review the available data from the Owens Valley to see what we might be able to deduce about this relationship.

SECTION 2. DATA FROM PERMANENT MONITORING SITES

Description of Permanent Monitoring Site Program

LADWP and ICWD began a cooperative vegetation monitoring program at permanent locations in the late 1980s. Data collected include DTW on a monthly basis and vegetation cover on an annual basis. These data provide the most accurate data available in the Owens Valley to study the relationships between DTW and vegetation change. The high value of these data results from three facts. First, direct measurements, rather than estimates, of DTW are made. Secondly, these DTW measurements are spatially associated with vegetation cover data. Finally, the vegetation data are collected from permanent locations, thereby minimizing the effect of spatial heterogeneity in the vegetation data.

There are 30 permanent monitoring sites located throughout the Owens Valley. The 30 sites consist of 8 control sites and 22 wellfield sites. A control site is a site that is located in an area outside the effect of groundwater pumping. A wellfield site is a site located in an area where groundwater pumping has taken place. The permanent monitoring sites were established over a five-year period, with data collection from the first ones beginning in 1987 and data collection from the last ones beginning in 1991.

Each permanent monitoring site includes a 100-m long permanent line transect and an associated monitoring well. Vegetation cover data (transpiring cover, first- and all-hit methods) are collected along the line transect in June and July of each year using the point intercept method, with data collected at each point using a point-frame (Bonham 1989:120). Sampling is conducted at 30-cm intervals, for a total of 334 sample points per line transect. Data are collected by species. Percent cover is calculated by dividing the total number of hits (number of 30-cm sample points at which the species was encountered) by 334, and multiplying by 100. The analysis presented in this paper was performed using first contact data.

The locations of the monitoring wells vary in distance from their associated permanent line transects. Most are within 100 m of the transects and all are within 500 m. Depth to water is measured in each of the monitoring wells at intervals (usually monthly) throughout the year. For statistical purposes in this paper, we used an average annual DTW value for each monitoring well. This average is the mean of the DTW value for the month of June of a given year plus the values for the preceding 11 months (if data are available for all 12 months: July-June).

Comparisons can therefore be made between changes in DTW over time and changes in vegetation cover. There are complicating factors associated with making these comparisons. In experimental design, these complicating factors are known as confounding factors (John 1971:12-13, Reader 1992). For example, 10 of the monitoring sites were fenced to exclude grazing by livestock and 20 were unfenced. Therefore, the effect of livestock grazing on the vegetation is a confounding effect, being present at 20 of the sites and not present at 10 sites. Although the correlation between DTW and vegetation cover are not equally simple for each monitoring site because of these confounding factors, these data do provide the best available data in the Owens Valley to study the relationships between changes in these two variables.

Examples of Relationships Between DTW and Vegetation

A simple way to begin the investigation of the relationship between DTW and vegetation using these permanent monitoring site data is to graph the two variables on the same graph and visually compare how changes in the graphs of the two variables compare. This is a common first-step in analyzing data (Skane 1985:29), especially time-series data (Roberts 1992:33).

Graphing DTW and total perennial cover for each of the monitoring sites results in 30 graphs. Adding the cover of each perennial plant species adds another 144 graphs. Presenting 174 graphs, even 30 graphs, much less discussing each one, is beyond the scope of this document. Instead, we present and discuss only a few of the graphs. The selected graphs illustrate relationships between DTW and vegetation that are intuitive (i.e., expected in most cases) and those that may be counter-intuitive (i.e, unexpected).

The intuitive relationship between DTW and vegetation is that as groundwater comes closer to the surface, vegetation cover will increase. Conversely, as groundwater becomes deeper, vegetation cover will decrease. Intuitively, this should be even more true for species with shallower root systems (e.g., grasses) than for species with deeper root systems (e.g., shrubs). In statistics, these expected responses can be termed the "hypothesis". It is the hypothesis, or the expected response, that is to be tested (Li 1964:51-52, Snedecor and Cochran 1989:11-12). The hypothesis would be deemed to be correct ("supported" in statistical jargon) if cover increased as DTW decreased (i.e., water came closer to the surface) or cover decreased as DTW increased (i.e., groundwater became deeper). Conversely, the hypothesis would not be supported (i.e., rejected) in those cases where cover decreased as DTW decreased or where cover increased as DTW increased.

Figure 5 presents data from some of the sites that support the hypothesis. Each graph presents DTW data (in meters) plotted as a dashed line and cover (%) data for one of the five major species of plants in the Owens Valley or for total perennial cover (%). Figure 5A shows changes in DTW and cover of Nevada saltbush (ATTO) at the Big Pine 1 (BP-1) monitoring site. Nevada saltbush is a shrub. The pattern of the changes in saltbush cover follows the pattern of change in DTW. In general, as DTW decreased (groundwater closer to the surface), saltbush cover increased (1992-1999), and as DTW increased (groundwater became deeper), saltbush cover decreased (1999-2002). Even though this general pattern held, there were variations in saltbush cover that could not be attributed to change in DTW. For example, between 1990 and 1992, DTW remained relatively stable but saltbush cover fluctuated substantially. Therefore, change in saltbush cover during this period cannot be attributed to change in DTW.

Figure 5B illustrates changes in rabbitbrush (CHNA), another very common shrub in the Owens Valley, at the Independence-Oaks Control 1 (IOC1) monitoring site. DTW decreased between 1989 and 2002, from a depth of about two meters (7 feet) in 1989 to 0.8 meters (3 feet) in 2002. As DTW decreased, rabbitbrush cover increased, from about 2% in 1989 to about 4% in 2002. Similarly, change in cover of greasewood (SAVE), another shrub, closely followed changes in DTW at the Big Pine 1 (BP-1) monitoring site (Figure 5C).

The two most common grasses in the Owens Valley are inland saltgrass and alkali sacaton. These two species have shallower root systems than do most shrubs, therefore the intuitive assumption is that cover of these grasses should more closely follow changes in DTW than do the shrubs. Figure 5D illustrates this expected response. Change in saltgrass (DISP) cover at the Bishop Control 3 (BSC3) site closely mimics the pattern of changes in DTW. Similarly, the pattern of change in sacaton (SPAI) cover is similar to the pattern of change in DTW at the Laws 3 (LW-3) monitoring site (Figure 5E). Change in total perennial cover (TPC) also has a similar pattern to change in DTW at Laws 3 (Figure 5F).

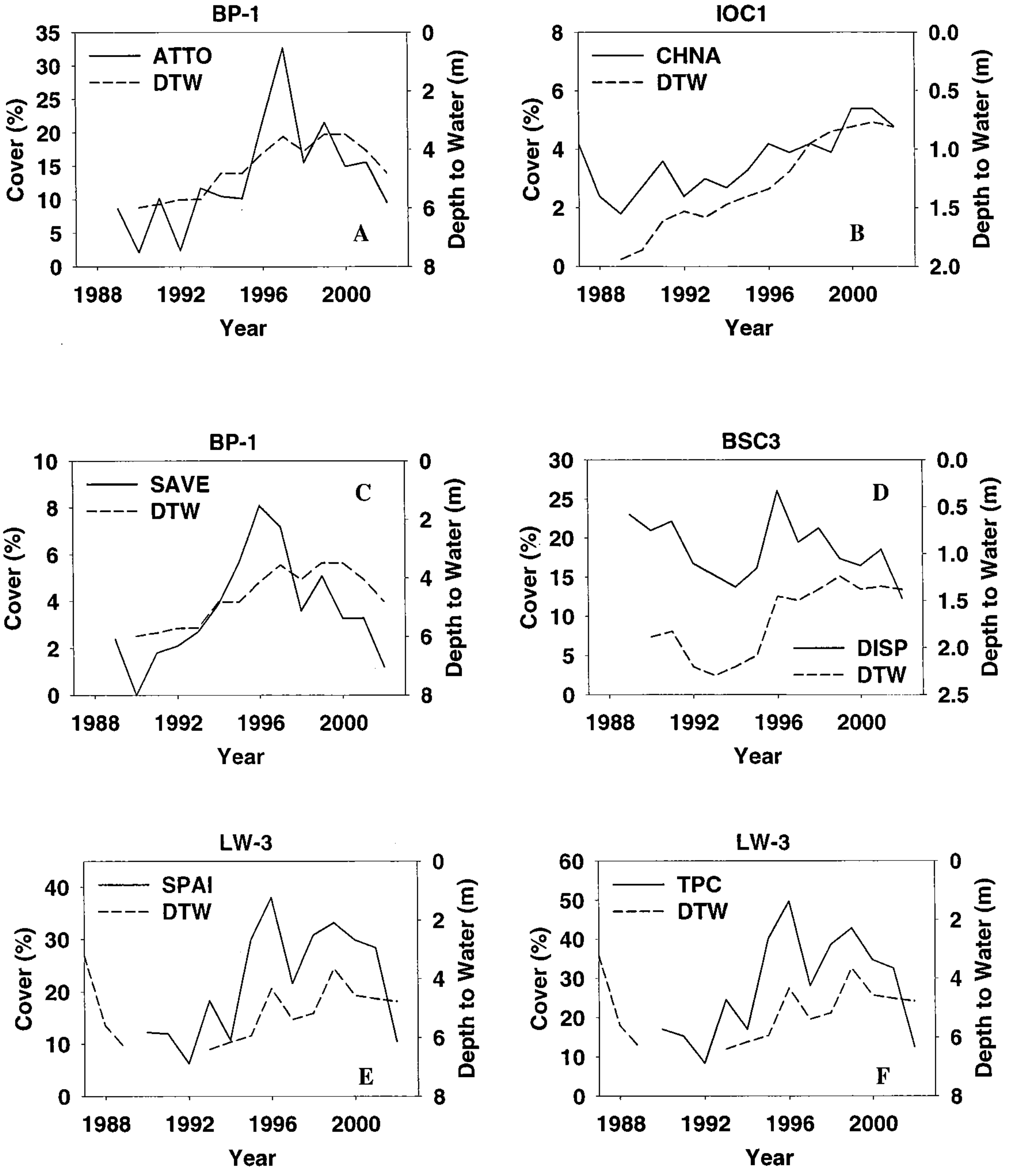

Figure 5. Six examples (A-F) of annual changes in DTW (m) and vegetation cover (%) that support the hypothesis.

These six examples provide support for the hypothesis, i.e., vegetation cover increases as DTW decreases and cover decreases as DTW increases. However, there are also numerous examples that refute the hypothesis, for the very same species that showed support for the hypothesis. At the Thibaut-Sawmill 4 (TS-4) site, DTW remained fairly constant from 1990 to 1995, gradually increased from 1995 to 1999, and then remained fairly constant through 2002 (Figure 6A). During this entire period, DTW decreased form about 3 m (10 feet) to about 2.4 m (8 feet). In contrast, cover of Nevada saltbush (ATTO) increased from about 1% in 1990 to about 9% in 1995, and then fluctuated from 1995 through 2002. Between 1997 and 2002, saltbush cover decreased from a high of over 12% to a low of less than 6%, despite DTW being constant during this period. These 10-fold changes in saltbush cover cannot be explained on the basis of change in DTW, because DTW remained relatively constant during this period.

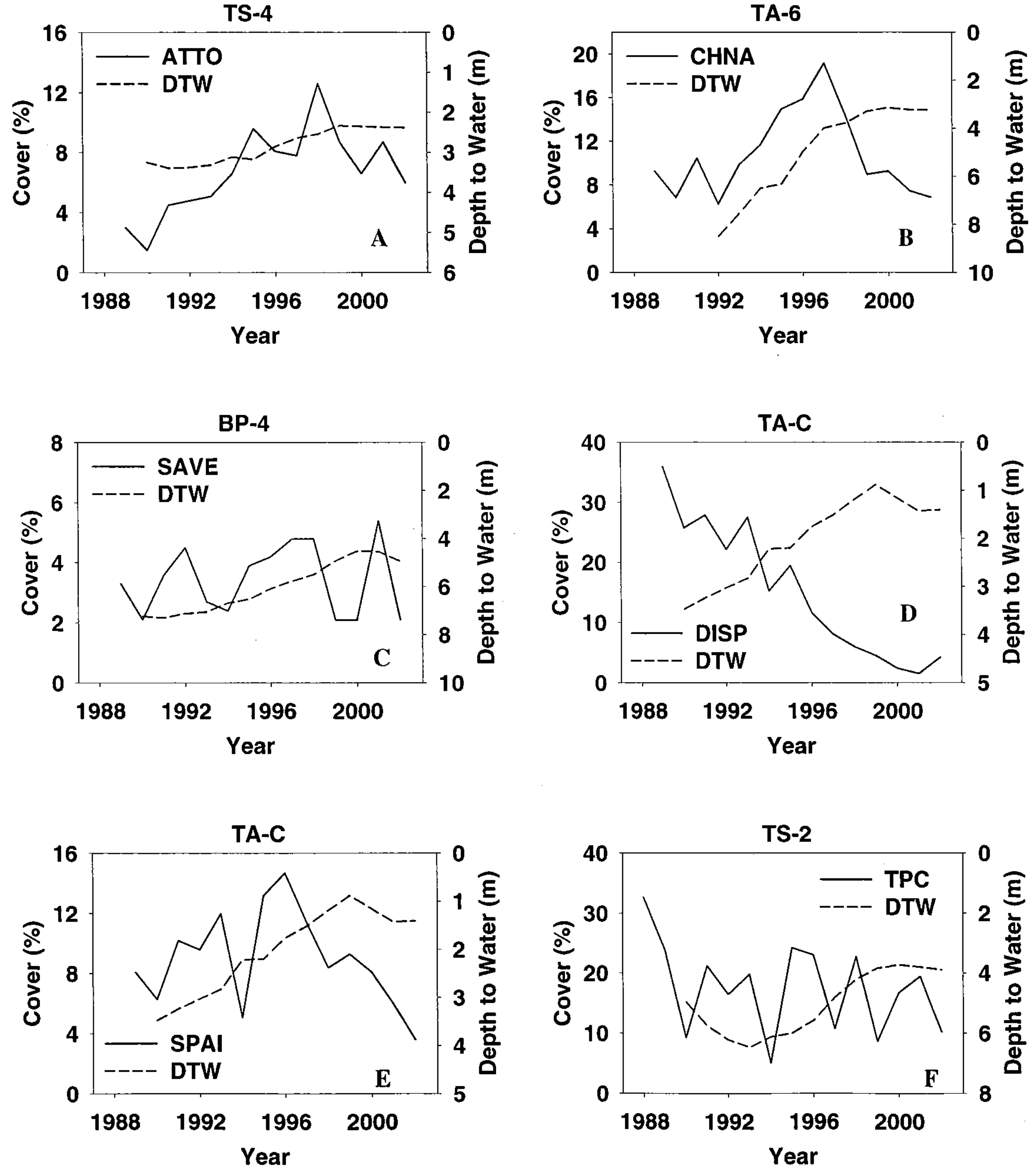

Figure 6. Six examples (A-F) of annual changes in DTW (m) and vegetation cover (%) that refute the hypothesis.

Data from the Taboose-Aberdeen 6 (TA-6) site illustrate the complexity of the ecological response of vegetation to changes in DTW. Between 1992 and 1997, changes in DTW and rabbitbrush cover appear to support the hypothesis. DTW decreased and rabbitbrush cover increased (Figure 6B). After 1997, DTW continued to decrease, but rabbitbrush cover decreased sharply (70% decrease) from 1997 to 2002. This is the opposite response to what would be expected from the hypothesis being correct. In addition, there is a complicating factor related to rooting depth. The Green Book (1990) uses a maximum effective rooting depth of 4 m for shrubs, including rabbitbrush. The positive response of rabbitbrush to change in DTW at TA-6 was when DTW was greater than 4 m (Figure 6B). This would have been when few roots were supposedly in contact with groundwater. Groeneveld (1990) reported that the effective rooting depth of rabbitbrush is about 4.7 m. The data from TA-6 would suggest that the effective rooting depth of rabbitbrush is even deeper than 4.7 m, perhaps as much as 7 m (Figure 6B). However, most rabbitbrush roots are probably within the top 4 m of the soil profile (Groeneveld 1986). Once groundwater came within this area of abundant roots (less than 4 m), rabbitbrush cover decreased dramatically. This again demonstrates that higher groundwater does not necessarily benefit vegetation.

There was a gradual decrease in DTW at the Big Pine 4 (BP-4) site from 1990 through 2000, followed by a gradual increase between 2000 and 2002 (Figure 6C). During this period, cover of greasewood (SAVE) fluctuated sharply, increasing from 2% to over 4% and then decreased back to 2%, three different times. Obviously, these fluctuations in cover were not the result of change in DTW because DTW gradually increase during most of this period.

DTW has steadily decreased (water table has risen) at the Taboose-Aberdeen Control (TA-C) site (Figure 6D). In 1990, it was about 3.5 m (11 feet) and in 2002 it was about 1.5 m (5 feet). In 1990, the site supported about 25% cover of saltgrass (DISP). Saltgrass cover has steadily declined since then, even as DTW has decreased. There are two possible explanations of what is causing the decline in saltgrass at this site. One is that the rising water table is detrimental to saltgrass. Although this is supported by the data, it is not likely to be true. Saltgrass is a species adapted to conditions of high soil moisture (Weaver and Clements 1938:467, Daubenmire 1978:224, Hickman 1993) and therefore should not have been adversely affected by the rising water table. The alternative explanation is that some other environmental factor is causing the decline in saltgrass. TA-C is a fenced site, so livestock grazing is not likely to be the cause of the decline. Nevada saltbush has increased substantially at this site, therefore competition from this shrub species may be at least part of the cause of the decline in saltgrass. Whatever the cause, and there may well be a combination of factors involved, it is not decline in water table.

Sacaton responded at the TA-C site in a manner similar to saltgrass (Figure 6E). Between 1990 and 1996, sacaton cover generally increased as DTW decreased, a pattern supporting the hypothesis. An exception was in 1994 when there was a substantial decrease in sacaton cover at a time of a continuing decrease in DTW. In 1996, DTW reached 2 m (7 feet) and continued to decrease. According to the above hypothesis, sacaton cover should have continued to increase because groundwater was becoming nearer the surface. However, the opposite response occurred. Sacaton cover decreased over the next six years, even as DTW continued to decrease.

At Thibaut-Sawmill 2 (TS-2), DTW increased between 1990 and 1993 and decreased between 1993 and 2002 (Figure 6F). Throughout this period, total perennial cover (TPC) fluctuated from year to year, with no overall trend. Three of the six high points in TPC cover occurred during periods of decreasing DTW. Three of the four low points in TPC occurred during periods of decreasing DTW and only one occurred when DTW was increasing. This pattern does not support the hypothesis.

These examples, some of which support the hypothesis and some of which refute the hypothesis, illustrate the danger in over-simplifying the response of vegetation to change in DTW. This is not to imply that, in general, there is not a positive relationship between available moisture and vegetation cover for most species. It does indicate that this relationship is often complex, and that there is no simple direct relationship between DTW, as a single factor, and vegetation cover. In other words, changes in vegetation cover cannot be explained, in a consistent manner, simply on the basis of increasing or decreasing DTW.

Statistical Relationships Between DTW and Vegetation

Graphical presentations, such as those in Figures 5 and 6, are very useful for an initial review of the data. They may clearly illustrate patterns in the responses of the two variables, and therefore suggest relationships. However, two major weaknesses in these graphical presentations are that 1) each graph illustrates a particular example and 2) the graphs do not provide a means to determine how important or significant the relationships are. Statistics provides a means to both summarize the results and to determine significance of various relationships.

There are many statistical methods that can be applied to ecological data such as these monitoring data to summarize and to statistically test whether or not our hypothesis is likely to be true or false. Each appropriate statistical test has its merits and no one test is better than others for all purposes. It should also be remembered that statistics are not designed to prove anything, in part because most statistical tests are based on probabilities. Statistical tests are designed as tools to help us evaluate the meaning of our data. Statistics are a supplement to, not a substitute for, good scientific logic.

Our purpose is to better understand the ecological relationship between changes in DTW and changes in vegetation cover. Our purpose is not to prove or disprove one hypothesis or another. Instead, we would like to test our hypothesis to determine how valid or how robust it is. How well does it fit the data? How well does it explain what the data imply is happening? The better we understand our currently available data and the hypotheses resulting from these data, the better we can know their limitations, and therefore the better we can design new studies to improve our understanding of these ecological relationships.

Our hypothesis is that there is an inverse relationship between DTW and vegetation cover, i.e., vegetation cover increases as DTW decreases, or cover decreases as DTW increases. One way to test this hypothesis is to tabulate how often the data support the hypothesis and how often the data refute the hypothesis. A Sign Test provides a simple, but effective, means to accomplish this objective (Snedecor and Cochran 1989:138).

There are 30 permanent monitoring sites. DTW and vegetation cover data have been collected from each of these sites over a number of years. Each annual data entry for each monitoring site therefore provides one observation that can be used to test our hypothesis. If for that monitoring site, DTW increased and cover decreased, our hypothesis has been supported by that observation (Table 2). We can assign a positive (+) to that observation. Likewise, if DTW decreased and cover increased, that observation also supported our hypothesis and we can also assign a + to that observation. Conversely, if DTW increased and cover increased, that observation would refute our hypothesis and we could assign a negative (-) to that observation. Likewise, if DTW decreased and cover decreased, we could also assign a negative to that observation. If there was no change in DTW and cover, we could consider that observation supported (+) our hypothesis.

Table 2. Possible Sign Test outcomes used to test relationship between change in depth to water (DTW) and change in cover (COV).

Supports or Refutes Hypothesis	Change in DTW (Depth to Water)	Change in Cover (Cover)
Supports	-	+
Supports	+	-
Supports	0	0
Refutes	+	+
Refutes	-	-
Refutes	0	+
Refutes	0	-
Refutes	+	0
Refutes	-	0

A minus sign (-) indicates a decrease.
A plus sign (+) indicates an increase.
A zero (0) indicates no change.

Four other outcomes are possible. DTW could increase or decrease and cover could remain the same, or DTW could remain the same and cover could increase or decrease. We considered that each of these four cases refuted the hypothesis because, in the first two cases, the change in DTW had no effect on cover and the hypothesis stated that it would and in the second two cases cover changed but DTW did not. Because cover changed and DTW did not, vegetation change could not be attributed to change in DTW.

In all cases, we tabulated only change in direction, not magnitude of the change. We rounded the data to one decimal place. No change (0) therefore was defined as the values (either cover or DTW) between two consecutive years being equal to one decimal place.

The permanent monitoring data set for the period 1987-2002 contains 379 observations (year x site combinations). Data collection did not begin at all sites in the same year. This complete set of 379 observations is available only for total perennial cover. Fewer observations are available for cover of individual species because not all species occur along all 30 transects. Once the number of observations within each category are summed, the totals can be used to evaluate the hypothesis. If most of the observations fall into those categories supporting the hypothesis, the hypothesis is likely to be true (Li 1964:53). However, it is still theoretically possible that it is false. On the other hand, if most of the observations fall into those categories refuting the hypothesis, the hypothesis in not likely to be true. And the magnitude of the difference between the number of observations supporting the hypothesis and the number refuting the hypothesis is a measure of the significance of result, or how much confidence we should put in our conclusion (Li 1964:53).

There is a total of 1354 observations that can be used to test the hypothesis (Table 3). Of these, 565 (42%) support the hypothesis and 789 (58%) refute the hypothesis. If the "no change" observations are excluded, 545 observations (50%) support the hypothesis and 552 (50%) refute the hypothesis. The conclusion reached from this test is that there is no difference between the two groups of observations. The hypothesis is supported half the time and the hypothesis is refuted half the time. Therefore, there is no consistent relationship between change in DTW and change in vegetation because each outcome has an equal probability of occurring (Snedecor and Cochran 1989:138), i.e., we would expect a 50:50 division of outcomes based on chance.

Table 3. Response of vegetation cover to change in depth to water (DTW) at 30 permanent monitoring sites in the Owens Valley. Values are number of years, summed over sites, where cover and DTW responded in the respective pattern.

Cover	Responses Supporting Hypothesis			Responses Refuting Hypothesis					
	DTW (-) COV (+)	DTW (+) COV (-)	DTW (0) COV (+)	DTW (-) COV (-)	DTW (+) COV (+)	DTW (0) COV (-)	DTW (0) COV (+)	DTW (+) COV (0)	DTW (-) COV (0)
TPRN	107	71	6	106	55	16	12	2	4
ATTO	70	34	3	68	33	16	20	1	4
CHNA	39	15	3	41	28	17	11	4	10
SAVE	36	20	4	35	18	10	11	5	6
DISP	29	28	1	53	22	13	15	3	13
SPAI	59	37	3	61	32	19	17	3	5
Total	340	205	20	364	188	91	86	18	42
%	25	15	2	27	14	7	6	1	3

Ho: As DTW decreases, cover should increase; as DTW increases, cover should decrease.
DTW = depth to water; COV = live leaf cover
TPRN = total perennial cover (%); ATTO = Nevada saltbush cover (%);CHNA = rabbitbrush cover (%); SAVE = greasewood cover (%); DISP = inland saltgrass cover (%); SPAI = alkali sacaton cover (%)

The Sign Test is a non-parametric test (i.e., not dependent on the mathematical distribution of the observations) that only considers the direction of the change, not the magnitude. Other statistical tests are available that also consider the magnitude of the change. One such test, commonly used to determine the statistical relationship between two variables, is correlation analysis (Skane 1985:270).

A total of 110 correlation analyses were conducted on the permanent monitoring data, one for total perennial cover for each of the 30 sites and one for each of the five major species at each site at which that species occurred. In each analysis, an observation consisted of the DTW value and the vegetation value for a given year. Sites where a species did not occur, or where it occurred in very low amounts (generally less than 0.5% average cover), were excluded from the analysis for that particular species.

The correlation coefficient (r) is a measure of the closeness, or strength, of the linear relationship between the two variables (Skane 1985:276, Snedecor and Cochran 1989:177). A value of 1 indicates a perfect fit between the two variables and a value of 0 indicates no relationship. Correlation coefficients can be either positive or negative. A positive r indicates that the two variables change in the same way, i.e., as one increases the other increases and as one decreases the other decreases. A negative r indicates that the two variables change in the opposite way, i.e., as one increases the other decreases.

One of the advantages in using correlation analysis is that the test is quantitative, i.e., it measures the magnitude or strength of the relationship. Because of this, statistical significance can also be measured. Statistical significance is based on probability. First, a desired level of probability is chosen. The level chosen is arbitrary, dependent on how much confidence one wants to put in conclusions drawn from the results of the statistical test. A commonly used level in plant ecology is 95%. This level indicates that the results of the statistical test will be correct 95% of the time. Conversely, there is a 5% probability (1 out of 20) that the conclusions will be incorrect. We used the 95% probability level in our analyses.

The 110 correlation analyses consisted of 30 for total perennial cover (one for each site), 22 for Nevada saltbush, 13 for rabbitbrush, 11 for greasewood, 15 for saltgrass, and 19 for sacaton. Of these 110 analyses, 38 (35%) were statistically significant and 72 (65%) were not statistically significant (Table 4).

These results indicate that we can be 95% confident that most of the time (65%), there is no relationship between DTW and vegetation cover. Most of the correlation coefficients were negative. This was true for the analyses overall (85 out of 110) and for the analyses that were statistically significant (35 out of 38). A negative correlation coefficient indicates that cover decreases as DTW increases, or that cover increases as DTW decreases. This is the expected pattern (i.e., DTW and cover are inversely related).

Of the five major species, the relationship between DTW and cover was significant most often for Nevada saltbush (11 out of 22 = 50%) and rabbitbrush (6 out of 13 = 46%)(Table 4). The relationship was least significant for greasewood (18%), saltgrass (20%), and sacaton (16%). Mean r values followed a similar pattern. On average, DTW and saltbush cover had a correlation coefficient of 0.49 and for rabbitbrush it was 0.47. For greasewood, the average r was 0.34 and for saltgrass and sacaton it was 0.32. These results indicate that DTW and vegetation cover are only weakly correlated.

Table 4. Correlation coefficients (r) between depth to water (DTW) and cover (%), total and for major species, at 30 permanent monitoring sites in the Owens Valley.

Site	Total Perennial	Nevada saltbush	Rabbitbrush	Greasewood	Inland saltgrass	Alkali sacaton
BG-2	-0.598 *	-0.698 *				-0.370
BG-C	-0.575 *	-0.529			-0.350	
BP-1	-0.816 *	-0.791 *		-0.655 *		
BP-2	-0.198	-0.221	-0.045			
BP-3	0.153			0.214	-0.398	-0.266
BP-4	-0.201	-0.443		-0.026		
BSC1	-0.315	-0.563 *	-0.298	-0.227	0.087	0.050
BSC2	-0.561 *	0.131	-0.657 *		-0.556 *	0.058
BSC3	-0.752 *		-0.754 *		-0.272	-0.118
IO-1	-0.671 *	-0.311	0.451			-0.755 *
IO-2	-0.006	-0.048				
IOC1	-0.730 *	-0.595 *	-0.856 *			
IOC2	0.173				0.516	0.358
LW-1	-0.697 *			-0.693 *		
LW-2	-0.283	-0.352	-0.561 *	-0.455	-0.351	-0.059
LW-3	-0.668 *	-0.408			-0.212	-0.729 *
SS-1	-0.629 *	-0.585 *		-0.464		
SS-2	0.062	0.657 *				
SS-3	-0.629 *	-0.617 *				
SS-4	-0.287	-0.110				
TA-3	-0.010	-0.249		0.038		0.230
TA-4	-0.763 *		-0.711 *		0.034	-0.708 *
TA-5	-0.141			0.168	-0.107	-0.423
TA-6	-0.528	-0.905 *	-0.199			-0.002
TA-C	0.185	-0.754 *			0.949 *	0.121
TS-1	-0.345	-0.502			0.318	-0.243
TS-2	0.084		-0.197		0.550 *	0.334
TS-3	-0.514	-0.699 *	-0.334		0.004	-0.408
TS-4	-0.639 *	-0.570 *	-0.581 *	-0.427	-0.147	-0.710
TS-C	-0.267		-0.516	-0.346		0.063
Mean	0.416	0.488	0.474	0.338	0.323	0.316

* Indicates statistical significance ($P < 0.05$).
Means are based on absolute values.

Significant correlation coefficients did not increase much when the data were separated by average DTW. Averaged over the five species, 33% of the correlations were significant when all depths to water were used (Figure 7). When only those sites with average DTW of 4 m or less were used, significant correlations increased to only 40%. When only those sites with average DTW of 2 m or less were used, significant correlations increased to 50%. These results suggest that, as DTW decreases (i.e., groundwater comes nearer the surface), the vegetation cover increases. Still, only half or less of the correlations are statistically significant. Interestingly, most of this increase in significance came from Nevada saltbush and rabbitbrush (Figure 7).

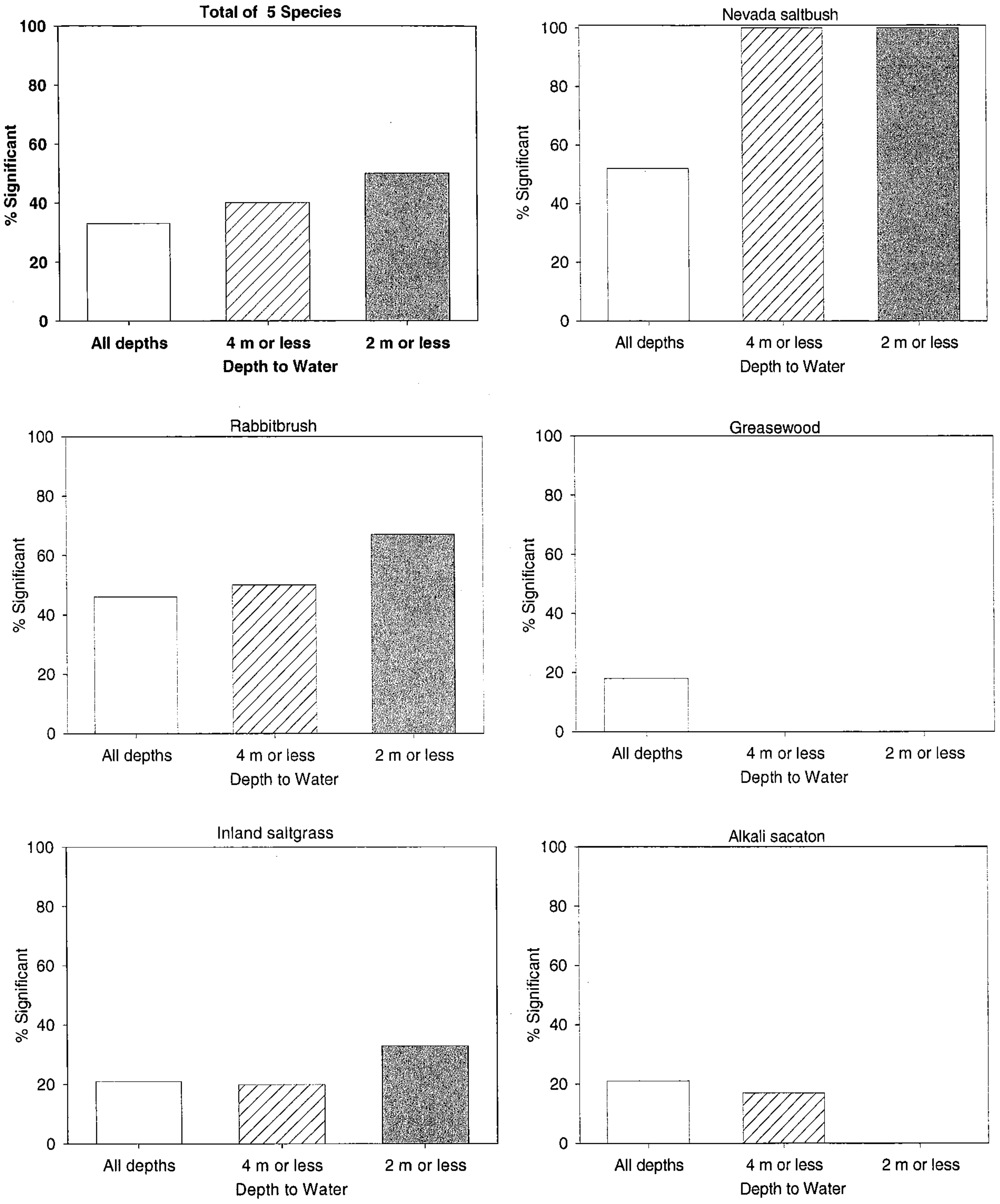

Figure 7. Effect of depth to water on the statistical significance of the correlation between change in DTW and change in total perennial cover at permanent monitoring site locations.

Summary

Most people prefer simple answers. Does the factor of interest matter or not? For many purposes, simple answers, if they are the correct answers, are the best answers. However, scientists often give answers that are not as simple as many people would like. This is especially true in ecology. Ecological relationships and ecological issues are often complex. Therefore, it should not surprise us when the answers to ecological questions are less than simple. The graphs presented in Figures 5 and 6 illustrate this truth. In some cases (i.e., at some permanent monitoring sites), there appears to be a simple relationship between DTW and vegetation change, while in other cases, the relationship is complex. And even where there is a simple relationship, this relationship is opposite at some sites from what it is at others. Therefore, it becomes difficult to make simple statements concerning the relationship between DTW and vegetation change. This can be very frustrating to many people, but it should not be surprising to the ecologist. Ecologists understand that vegetation change is influenced by a variety of environmental factors, of which DTW is only one. Therefore, unless each of the factors is properly measured, it is very difficult to properly allocate the effects of each factor on vegetation change.

Statistical analysis of the permanent monitoring site data support the same conclusion, i.e., there is no simple direct relationship between change in DTW and change in vegetation cover. A Sign Test indicates that change in DTW supports the expected hypothesis relating to change in vegetation only half of the time. The other half of the time, change in DTW refutes the hypothesis that a decrease in DTW will result in an increase in cover, or that an increase in DTW will result in a decrease in cover. Correlation analysis indicates that there is a statistically significant ($P < 0.05$) relationship between DTW and vegetation cover only about one-third of the time.

SECTION 3. DATA FROM ICWD ANNUAL MONITORING PROGRAM

The permanent monitoring data provide the best data set to analyze the relationship between DTW and vegetation cover in the Owens Valley, but it is not the only data set. ICWD has sampled vegetation cover at a number of sites each summer since 1991. These data can be used to supplement the permanent monitoring site data to evaluate the relationship between DTW and vegetation cover.

The ICWD vegetation monitoring program uses line point transects to sample the vegetation in selected parcels. A parcel is an area containing vegetation that is assumed to be relatively homogeneous. LADWP established these parcels on their lands and mapped the vegetation in the 1980s. Each year, ICWD selects a varying number of these parcels and randomly locates 50-m line transects in the parcels and samples the vegetation cover along these transects.

Measured DTW data are not available to compare to most of these transects. However, estimated DTW data are available. These DTW estimates are generated through a technique called kriging (Harrington 2003). These data are discussed in more detail in the following subsection of this report.

The advantage in using the vegetation monitoring data collected by ICWD is that they cover a broader area than do the permanent monitoring data. There are only 30 permanent monitoring sites for all of the Owens Valley. In comparison, there are over 1700 parcels supporting native vegetation. ICWD has collected vegetation data from 137 of these parcels, but not from all 137 parcels in all years. Data from these 137 parcels provides for a more extensive spatial sampling than do the 30 permanent monitoring sites.

There are also disadvantages in using the ICWD-collected annual monitoring data. One disadvantage is that the DTW data are estimates. There is always additional error in estimates, compared to direct measurements. Whenever possible, the magnitude of this error should be determined and accounted for in any resulting interpretation of data that includes these estimates.

A second disadvantage is that the vegetation data are collected from different locations each year. This is the result of the fact that the same parcels are not always sampled each year and when the same parcels are sampled in subsequent years, the transect locations are re-randomized each year. The randomization of transects does not pose a disadvantage in comparing DTW and vegetation cover within a single year. However, it does present the disadvantage of including spatial heterogeneity in the data when comparing across years. This error or "noise" in the data should also be accounted for when interpreting results.

In summary, these data collected by ICWD provide another data set that can be used to evaluate the relationship between DTW and vegetation cover. These data have the advantage of being more spatially diverse than the permanent monitoring site data, but have the disadvantage of increased sampling error ("noise") associated with the estimation of the DTW values and a spatial heterogeneity effect incorporated in the vegetation data.

Kriging Data

Measured DTW data are not available for most locations within most parcels. Therefore, to compare vegetation data to DTW in most locations, some type of estimated DTW values are required. Kriging is a method of estimating depth to water. The process takes measured values from wells and uses statistical techniques to average these values across the landscape based on relative distances to the measured points. Two kriging methods used by ICWD are the space-time ordinary kriging (OK) and the space-time kriging with an external drift (KED) (Harrington 2003).

The two methods provide similar values, but the values differ somewhat in some cases. We compared the average DTW values between the two methods for the 65 parcels re-inventoried by ICWD in 2003. On average, the two methods had an 87% similarity (mean ratio of the average DTW values of the two methods was 0.874). We also estimated the accuracy of the kriging estimates of DTW by comparing them to measured values from wells associated with the permanent monitoring sites. We did this by first calculating an average kriging DTW value for those parcels that also contained a montoring well associated with a permanent monitoring site. This value was the average of the two methods, using all reported values within the given parcel. We then calculated an accuracy ratio for each parcel by dividing the smaller of the two values (average kriging DTW value or measured DTW from monitoring well) by the larger of the two values. These accuracy ratios varied between a low of 39% to a high of 99.7%, with an average of 82%.

Neither method was consistently more accurate than the other. We used values from the OK method in our analysis.

Spatial Analysis of Parcel Data

ICWD has collected vegetation cover data from a total of 137 parcels. Data have been collected in each year since 1991 from 18 of these parcels and for some years since 1991 in the other 119 parcels. In all, there are 1089 parcel-year combinations (data from a parcel in a given year) in the ICWD data set between 1991 and 2003. As with the permanent monitoring data, there are too many possible combinations to be included in the scope of this report. Instead, we present examples that support the hypothesis that vegetation cover increases as DTW decreases or that cover decreases as DTW increases, and examples that refute the hypothesis.

The vegetation of parcel PLC 223 (Poleta Canyon 223) consists of mosaic of alkali sacaton, rabbitbrush, and Nevada saltbush, with lesser amounts of greasewood and inland saltgrass. In 2001, estimated DTW varied across the parcel from 11 feet to about 20 feet, and total perennial cover varied from 9 to 52% (Figure 8). Deeper groundwater (18-20 feet) was located along the northeastern portion of the parcel and shallower groundwater (10-13 feet) was located along the southwestern portion of the parcel. In general, the northeastern portion of the parcel, the area corresponding to the greater DTW, had lower total perennial cover values (9-21%) than did the southwestern portion (28-52%), which corresponds to the area of shallower DTW. The relationship between DTW and cover is not absolute. For example, in the east-central portion of the parcel, there was a cluster of three transects with estimated DTW varying between about 14.5 and 16.5 feet. The transect with a cover value of 35% had an estimated DTW of about 14.5 feet, the transect with a cover value of 13% had an estimated DTW of 15 feet, and the transect with a cover value of 16.5 feet had a cover value of 34%. However, in general, the expected relationship between deeper DTW and less cover held for this parcel in 2001.

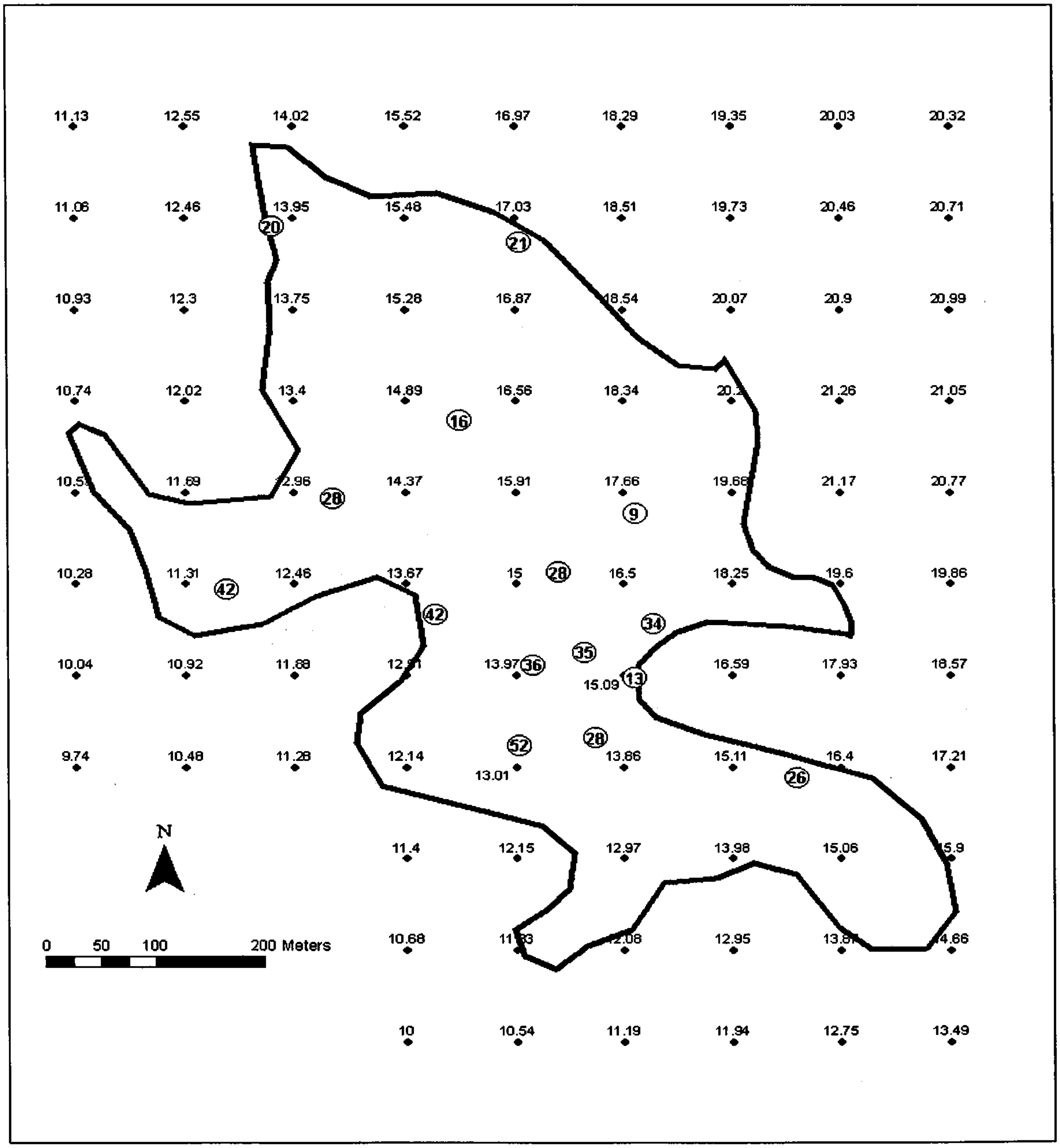

Figure 8. Map of the parcel PLC 223 showing percent total perennial cover (circles) and estimated DTW (in feet) in 2001.

This expected relationship between DTW and cover in PLC 223 weakened in 2002. That year, DTW values remained about the same as in 2001, with the same pattern (Figure 9A). The northeast portion had the deepest DTW values (17-20 feet) and the southwest portion the shallowest (11-14 feet). The lowest cover values (1-9%) were still mostly in the northeastern portion and the highest cover values (19-34%) were in the west-central region. However, there were low cover values (8%) and high cover values (34%) associated with the same DTW values (14.5 feet). The pattern continued to be weak in 2003 (Figure 9B). The lowest cover values were 7%, 11%, 13%, and 15%. These cover values were associated with DTW values of 17 feet, 13 feet, 16 feet, and 18 feet. The highest cover values (34%, 38%, and 47%) were associated with estimated DTW values of 13-15 feet. Therefore, some of the lowest cover values had the same DTW values as some of the highest cover values.

The average estimated DTW for PLC 223 in 2001 was 15.1 feet (Figure 8). DTW remained about the same (15.2 feet) during 2002 and 2003 (Figures 9A and 9B). In 2001, total perennial cover averaged 29%. This decreased to 15% in 2002, and then increased to 22% in 2003. These changes in vegetation cover cannot be attributed to change in DTW because DTW remained stable during this period.

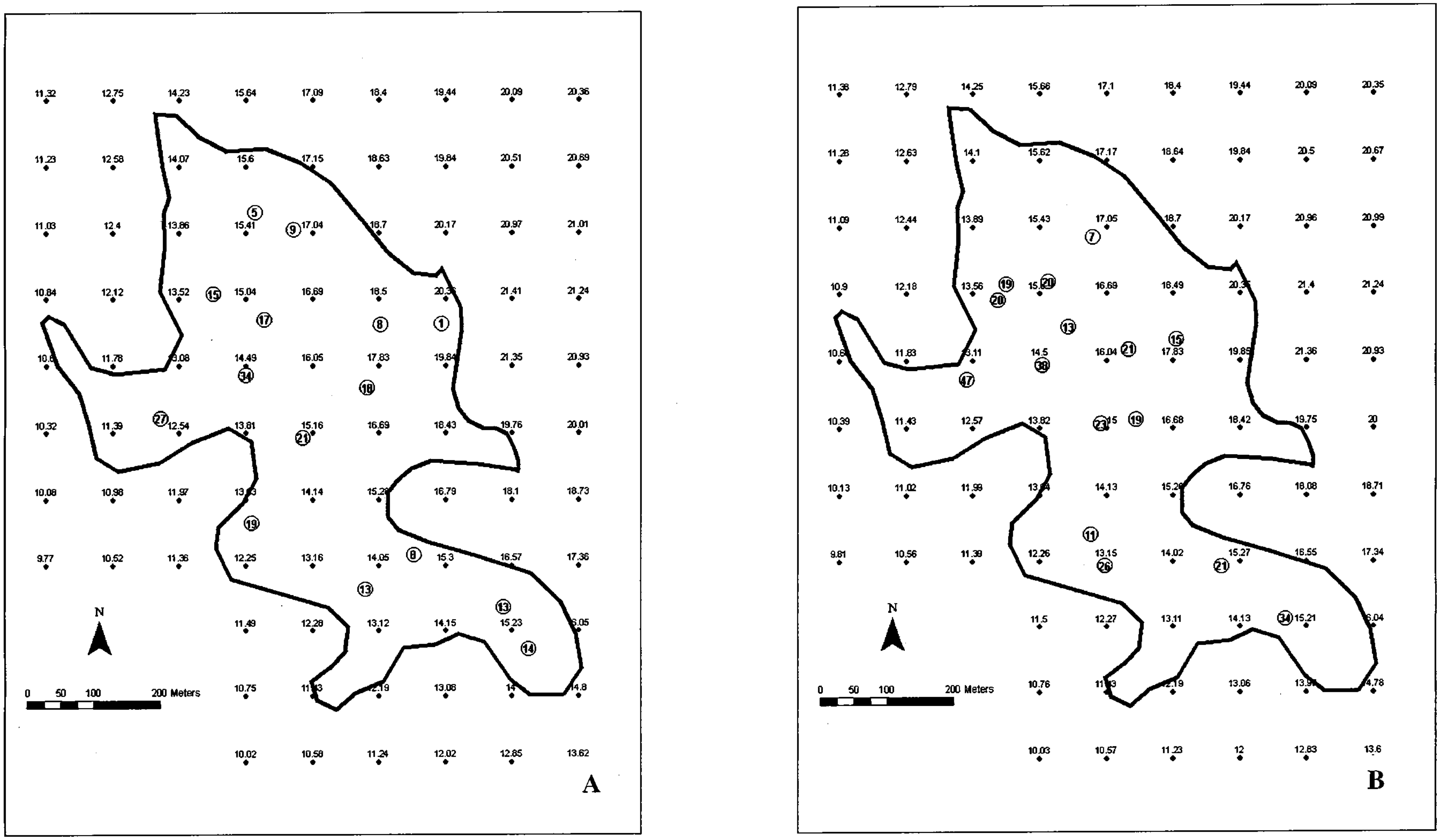

Figure 9. Map of the parcel PLC 223 showing percent total perennial cover (circles) and estimated DTW (in feet) in 2002 (A) and 2003 (B).

IND 139 (Independence 139) is a parcel in which DTW increases from the southeast to the northwest (Figure 10). In 2001, estimated DTW averaged 4-9 feet in the southeast and 12-30 feet in the northwest. The vegetation in IND 139 is a mixture of shrubs (mostly Nevada saltbush), with some grasses (mostly alkali sacaton). In 2001, the areas where groundwater was nearest the surface (i.e., low DTW values; 4-9 feet) had total perennial cover values mostly of 24-44% (Figure 10). Areas where groundwater was deepest (DTW = 12-30 feet) had cover values of 11-24%. This pattern, in general, supports the hypothesis that cover increases as DTW decreases. However, there were exceptions to this general pattern. There was an area of low cover (10%) in an area were estimated DTW was 4-5 feet and the highest cover value (52%) was in an area with an estimated DTW of 10-13 feet (Figure 10).

Estimated DTW in IND 139 averaged 10.1 feet in 2001. This decreased to 9.6 feet in 2002 and 9.7 feet in 2003. Total perennial cover averaged 26% in 2001, decreased to 18% in 2002, and then increased to 35% in 2003. These changes in vegetation cover were not the result of changes in DTW. DTW decreased (groundwater was closer to the surface) between 2001 and 2002, but total perennial cover also decreased. Total perennial cover almost doubled between 2002 and 2003 while DTW increased slightly. Therefore, some factor, or factors, other than DTW was controlling this change in vegetation cover.

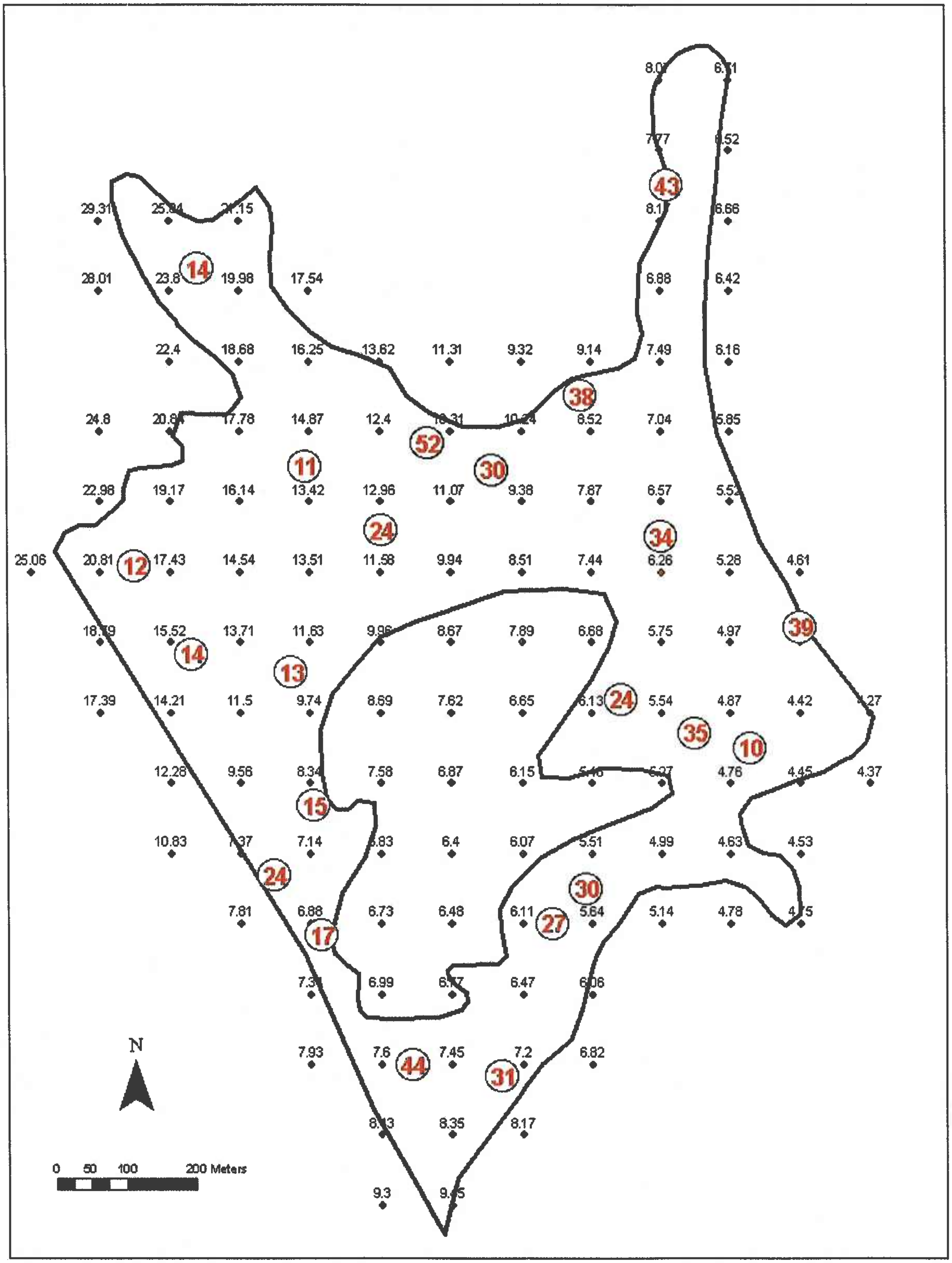

Figure 10. Map of the parcel IND 139 showing percent total perennial cover (circle) and estimated DTW (in feet) in 2001.

The distribution of total perennial cover in 2001 in PLC 223 and IND 139 mostly support the hypothesis that there is an inverse relationship between DTW and vegetation cover. There are numerous examples of where the data refute the hypothesis. Two examples are presented to illustrate this response.

Groundwater at BLK 099 (Blackrock 099) is shallower (DTW = 3.5-5.5 feet) along the eastern portion of the parcel and deeper (DTW = 9-13 feet) along the western portion of the parcel (Figure 11). Six vegetation sampling points were located along the eastern portion in 2001. Total perennial cover at three of the points averaged 56% (54%, 59%, and 56%) and three averaged 22% (19%, 31%, and 15%). Estimated DTW in the area averaging 56% cover was 3.4-4.1 feet. Estimated DTW in the area averaging 22% cover was 3.7-4.4 feet. Near the center of the parcel, in an area with an average estimated DTW of 4.8-5.2 feet, total perennial cover averaged 72%. Four transects located in the most northwestern portion of the parcel, in a region of 7-11 feet estimated DTW, averaged 42% cover, or almost twice as much in the area that averaged 3.7-4.4 feet estimated DTW. Finally, four transects in the southwestern portion of the parcel, an area with an estimated DTW of 9-12 feet, averaged 34% total perennial cover, and one of these four sampled areas had 16% cover while another had 61% cover. This distribution pattern for vegetation cover shows little, if any, relationship to DTW.

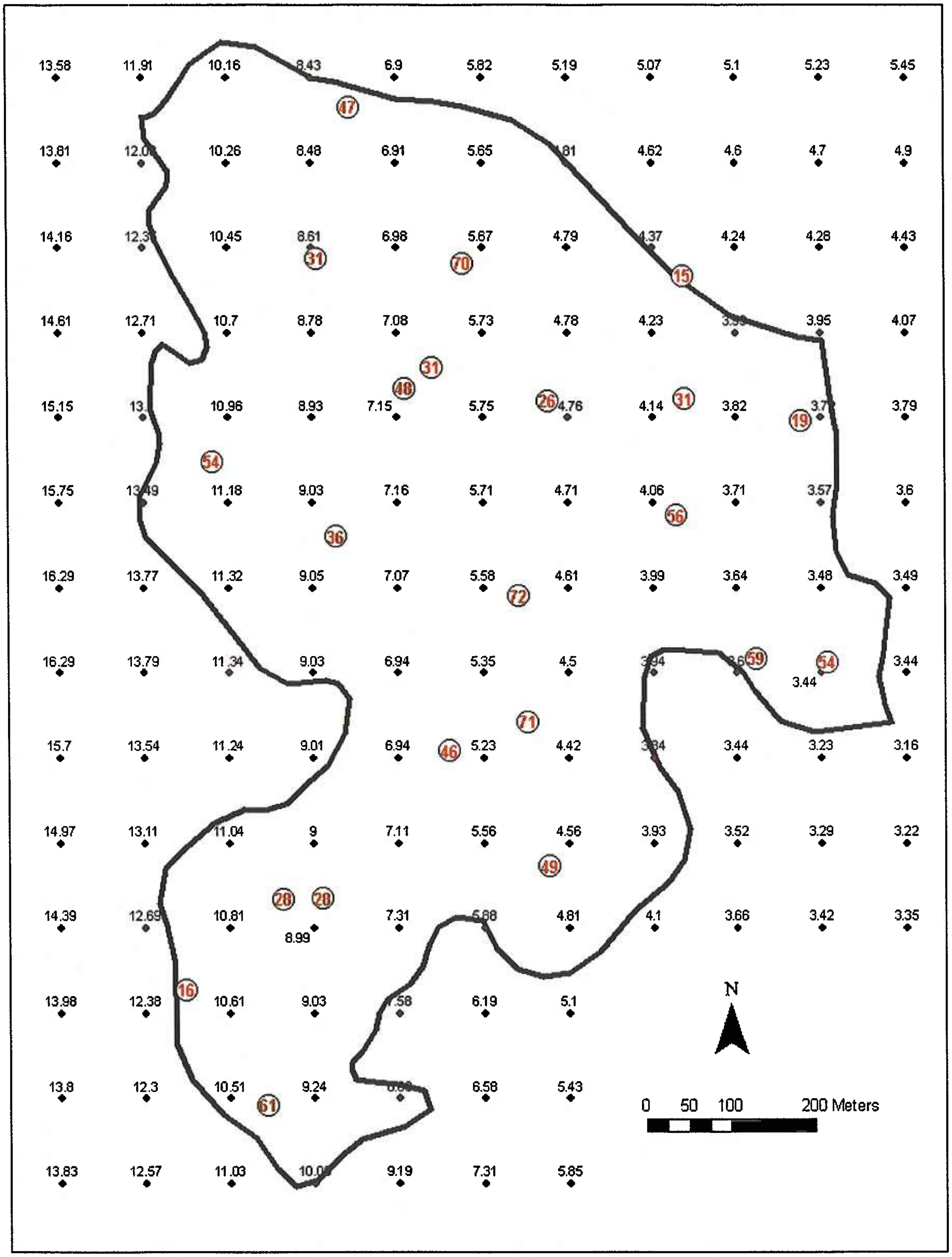

Figure 11. Map of parcel BLK 099 showing percent total perennial cover (circles) and estimated DTW (in feet) in 2001.

IND 111 (Independence 111) provides another example where the vegetation data and DTW data do not support the hypothesis. Estimated DTW varied in this parcel in 2001 between about 4.5 and 7 feet in the northeastern portion of the parcel and between about 13 and 24 feet in the southwestern portion of the parcel (Figure 12). Total perennial cover averaged 42% in the area with an estimated DTW of 4.5-7 feet and averaged 35% in the area with deeper groundwater (DTW = 13-24 feet). In 2002, estimated DTW in the northeastern portion varied between 4.5 and 8 feet and varied in the southwestern portion between 11 and 24 feet (Figure 13A). Total perennial cover that year averaged 21% where the groundwater was shallower and 27% in the area with deeper groundwater. This trend of decreasing cover in the area of higher groundwater and increasing cover in the area of decreasing groundwater continued in 2003 (Figure 13B). That year, the northeastern portion of the parcel had estimated DTW values between 4.5 and 9 feet, and the southeastern portion had values of 17-28 feet. Average total perennial cover in the northeastern area was 18% and average total perennial cover in the southwestern area was 34%.

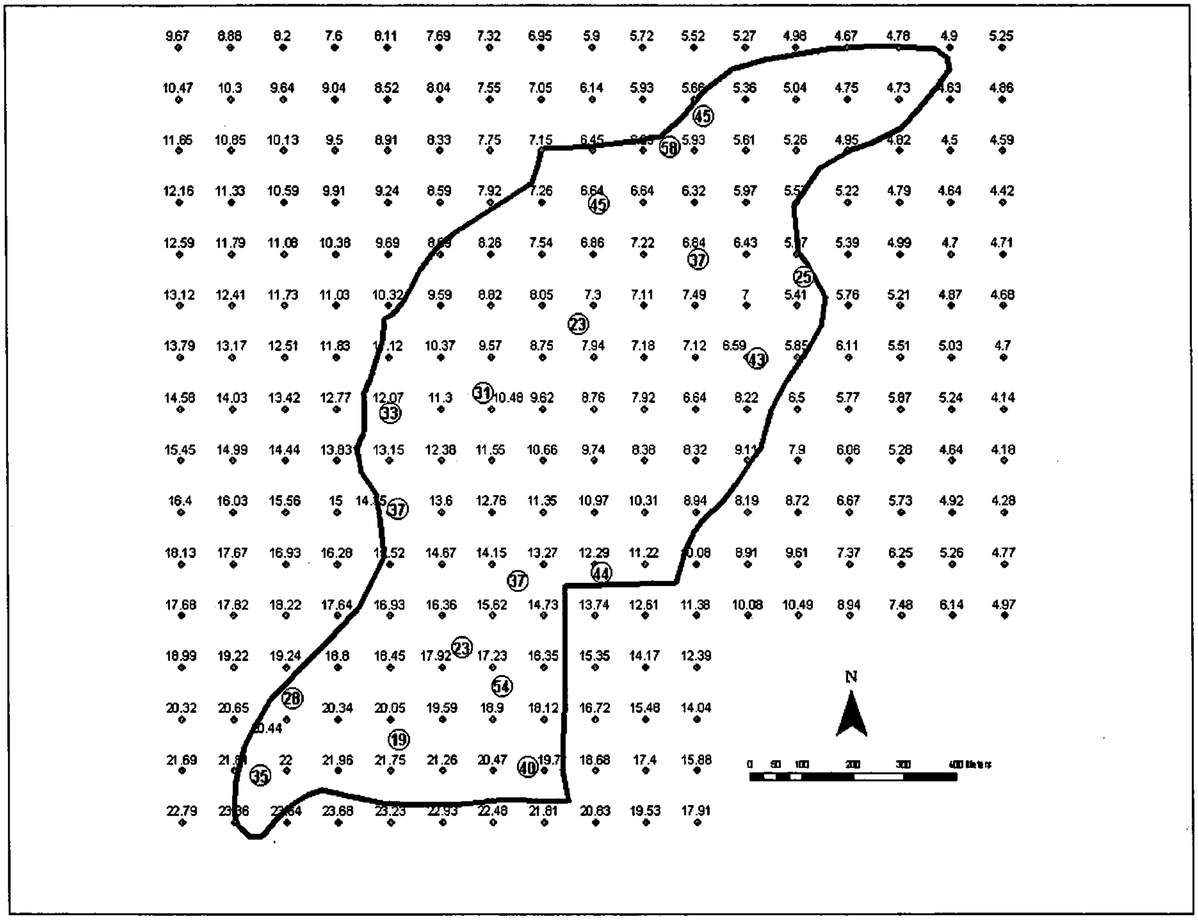

Figure 12. **Map of the parcel IND 111 showing percent total perennial cover (circles) and estimated DTW (in feet) and 2001.**

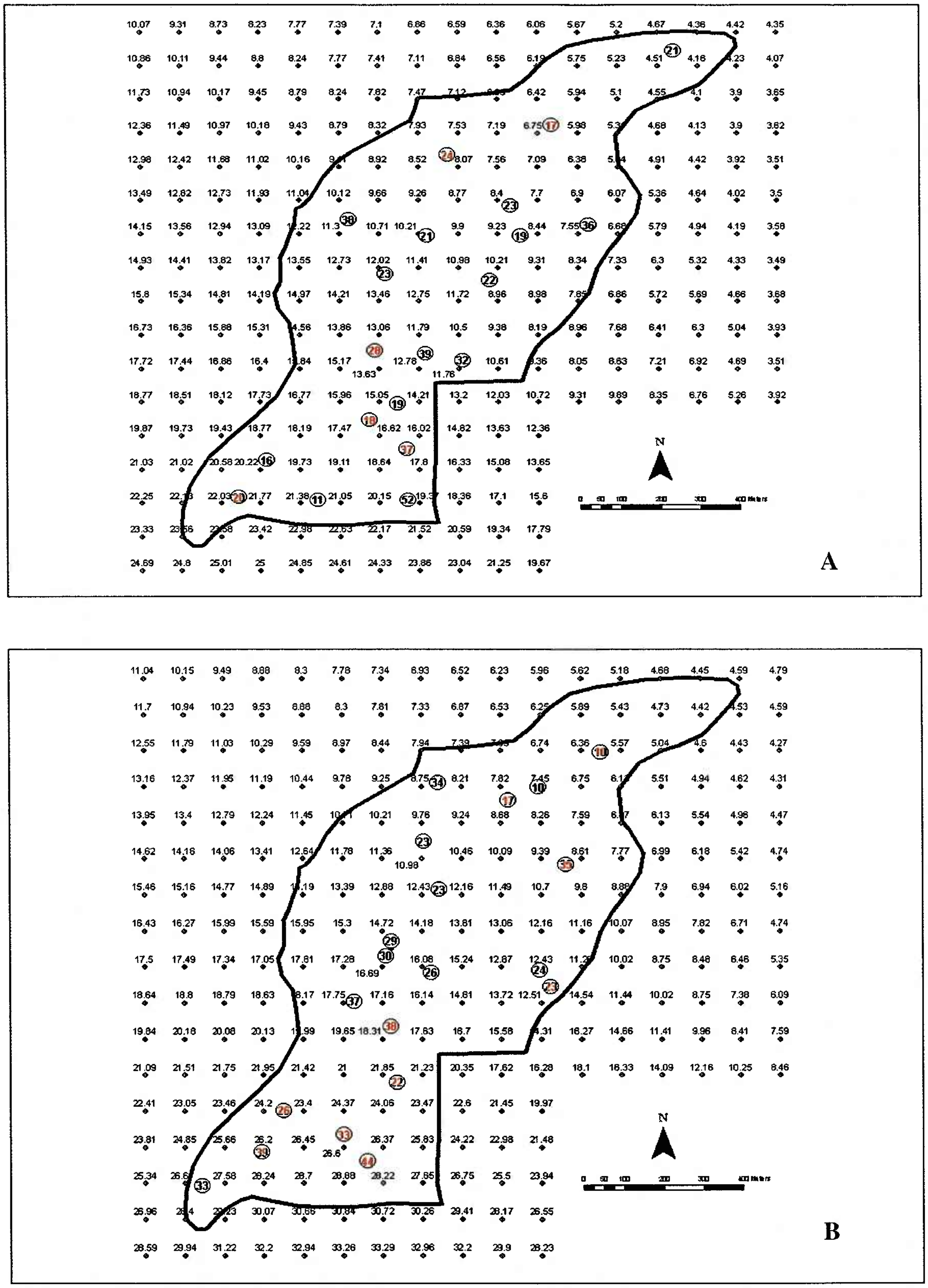

Figure 13. Map of parcel IND 111 showing percent total perennial cover (circles) and estimated DTW (in feet) in 2002 (A) and 2003 (B).

Therefore, between 2001 and 2003, estimated DTW in the northeastern portion of the parcel increased slightly (from 4.5-7 feet to 4.5-9 feet). Total perennial cover changed in this area from 42% in 2001 to 18% in 2003, or a decrease of 57%. Estimated DTW in the southeastern portion of the parcel, the area with deeper groundwater, increased (i.e., groundwater became deeper) by about 20% (13-24 feet in 2001, 17-28 feet in 2003). Total perennial cover in this area remained the same as it was in 2001. In this case (IND 111), both the vegetation distribution pattern within the parcel and the change in vegetation and DTW refute the hypothesis that higher groundwater should result in higher vegetation cover.

These four examples, two supporting the hypothesis and two refuting the hypothesis, were selected from a much larger set (137) of parcels. Other examples could be selected, other parcels and various years among parcels. Presenting all these combinations is beyond the scope of this paper. Instead, one method of arriving at a general metric of how well these data support or do not support the hypothesis is correlation analysis.

We used correlation analysis to evaluate the relationship between DTW and total perennial cover on 31 parcels, including the four used as the above examples. We conducted 389 correlation analyses, one for each year for each of the 31 parcels, one for each parcel combining all years, and one for all 31 parcels and all years combined.

Overall, DTW and total perennial cover had a correlation coefficient of – 0.26. This was for all 31 parcels and all years combined. This negative correlation coefficient indicates that as one variable increases, the other decreases. This fact supports the hypothesis. Although the correlation coefficient value is small (0.26), it is statistically significant ($P < 0.01$) because of the large number of observations included in the analysis (6262). However, even though the correlation is statistically significant, the low correlation coefficient value (0.26) indicates that less than 7% of the variation in total perennial cover is explained by variation in DTW.

Of the 31 parcels tested, correlation between DTW and total perennial cover was statistically significant in 22 of the parcels (71%; Table 5). Although there was a statistical relationship between DTW and total perennial cover in 70% of the parcels analyzed, this correlation did not explain a large amount of the variation between the two variables. The square of the correlation coefficient (known as r^2) is an estimate of the amount of the variance in one variable that can be attributed to its linear regression on the other variable (Snedecor and Cochran 1989:183). When r is 0.5 or less (equal to an r^2 value of 0.25 or less), "only a minor portion" of the variation in one variable can be attributed with the other variable (Snedecor and Cochran 1989:183). All but two (IND 011 and PLC 223) of the 31 correlation coefficients associated with DTW and total perennial cover were 0.5 or less, indicating that the relationship between the two variables was weak. On average, DTW explained only about 9% of the variation in total perennial cover in the 31 parcels, and in only 13 of the 31 cases (42%) was more than 10% of the variation explained.

Table 5. Results of correlation analyses between depth to water and total perennial cover conducted on data from 31 vegetation parcels in the Owens Valley.

Parcel	Years	Observations	Correlation Coefficient	Variation Explained (r^2)	Statistical Significance
BGP 162	12	233	- 0.500	0.250	0.01
BLK 009	12	250	- 0.287	0.082	0.01
BLK 016	12	261	- 0.412	0.170	0.01
BLK 024	11	214	0.054	0.003	
BLK 033	11	148	0.248	0.062	0.01
BLK 039	12	158	- 0.022	0.000	
BLK 075	11	209	- 0.358	0.128	0.01
BLK 094	12	229	- 0.318	0.101	0.01
BLK 099	13	255	- 0.240	0.058	0.01
BLK 115	12	190	- 0.020	0.000	
BLK 142	11	170	- 0.006	0.000	
IND 011	12	127	- 0.510	0.260	0.01
IND 035	12	181	- 0.117	0.014	0.10
IND 096	13	232	0.004	0.000	
IND 111	10	186	- 0.160	0.026	0.05
IND 139	12	155	- 0.360	0.130	0.01
IND 163	11	232	0.038	0.001	
LAW 063	13	192	- 0.446	0.199	0.01
LAW 065	11	138	- 0.235	0.055	0.01
LAW 120	12	151	- 0.443	0.196	0.01
LNP 018	12	204	- 0.070	0.005	
MAN 007	11	293	- 0.376	0.141	0.01
MAN 037	11	245	- 0.440	0.194	0.01
MAN 060	11	83	- 0.182	0.033	
PLC 024	11	139	- 0.164	0.027	0.10
PLC 121	11	186	- 0.415	0.172	0.01
PLC 137	12	158	- 0.365	0.133	0.01
PLC 223	11	164	- 0.505	0.255	0.01
TIN 028	11	234	- 0.234	0.055	0.01
TIN 068	10	162	0.127	0.016	
UNW 039	12	259	- 0.187	0.035	0.01
Totals	358	6262			
Mean				0.090	

These results indicate that there is a statistical relationship between DTW and total perennial cover, and this relationship is of the form that supports the hypothesis, i.e., cover increases and DTW decreases and cover decreases as DTW increases. However, this relationship is relatively weak. Only about 9% of the variation in total perennial cover can be explained by variation in DTW. Conversely, over 90% of the variation in total perennial cover is most likely the result of factors other than DTW.

SECTION 4. CONCLUSIONS

The relationship between change in DTW and change in vegetation cover is not a simple relationship. It is a complex ecological relationship involving a number of environmental factors in addition to DTW. These include species differences, composition of the vegetation (especially as it relates to competition among species), precipitation, grazing, history of land use, soil factors, successional dynamics, insect and pathogen impacts, and fire history. In their study of the effects of moisture factors influencing changes in herbaceous species along the San Pedro River in Arizona, Bagstad et al. (2005) found that changes in herbaceous perennials were controlled by an interaction of various factors, of which depth to groundwater was only one.

Vankat (1979:28) clearly stated the challenge when he wrote "Thus the problems of relating vegetation to environment are extremely complicated and pose an intriguing challenge for vegetation scientists." "All factors in an ecosystem are interrelated and a change in any one changes the relationship of all other factors in that ecosystem" (Stoddart et al. 1975:147). Daubenmire (1968:3) stated that plant communities are, in large part, "the products of interaction between two phenomena: 1) differences in the environmental tolerances (or ecological amplitudes) of the various taxa which comprise the flora and 2) the heterogeneity of environment." Daubenmire (1967:3) also pointed out that "The minimal, optimal, and maximal intensities of any one factor are not fixed, but vary according to other conditions under which the organism happens to be growing."

It has long been recognized that, although water supply is a critical factor in determining plant response, there is often no direct relationship between soil moisture content and plant response, in part because of confounding environmental factors (Kramer 1969:352). This is true for arid regions as well as for more humid regions. McNaughton (1991:325) strongly stated this conclusion in relation to understanding the dynamics of herbaceous perennials in dryland regions. "A better picture of the responses of dryland herbaceous perennials to stress, therefore, would come from focusing on the interactions between water stress and other factors, rather than exclusively on water stress."

Therefore, it should not surprise us that the effect of changes in one environmental factor, no matter how important it may be as a single factor, will vary depending on the interactions of other ecological factors. This is the message resulting from this document. Vegetation change in the Owens Valley is affected by changes in DTW, but the characteristics of this response, as well as the degree to which it occurs, varies from site to site. The hypothesis that there is a simple inverse relationship between change in DTW and change in vegetation is not supported by the available data that have been collected in the Owens Valley. As often as not, the data from the permanent monitoring sites refute this hypothesis. Likewise, there is no consistent correlation between DTW and total perennial cover. One-third of the time, this correlation is statistically significant. The other two-thirds of the time, it is not. The lack of a direct relationship between DTW and plant response has also been reported for riparian meadows in Nevada (Martin and Chambers 2001).

These results do not imply that DTW has no effect on vegetation. It does have an effect. However, this effect is modified by other ecological factors. At some sites, the relationship between change in DTW and change in vegetation is simple and is the relationship that supports the hypothesis that as DTW increases, vegetation cover decreases. At other sites, this inverse relationship is not supported by the data. Other factors are the primary factors causing vegetation change.

This complex response is entirely consistent with ecological theory. We stated earlier in this document that simple answers, when they are the correct answers, are generally the best answers. In the case of the relationship between DTW and vegetation change, simple answers are not the correct answers. However, a positive outcome of knowing this is that we can go forward and determine more about how other factors contribute to vegetation change in the Owens Valley. As stated by Vankat (1979:28) these complicated interactions pose an “intriguing challenge” to those interested in understanding the causes of vegetation change.

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