Independent Peer Review of
Tamarisk & Russian olive Evapotranspiration
Colorado River Basin

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Prepared by

Tamarisk Coalition

For

The Parties to the Memorandum of Understanding (MOU) to coordinate activities for tamarisk management activities in the Colorado River Basin. The Parties to the MOU are the Central Arizona Water Conservation District, Colorado Water Conservation Board, New Mexico Interstate Stream Commission, Six Agency Committee, Southern Nevada Water Authority, Utah Division of Water Resources, and Wyoming State Engineer's Office.

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This report was prepared solely by the members of the Peer Panel. The Tamarisk Coalition, a nonprofit organization whose mission is to provide technical assistance and education in support of the restoration of riparian lands, provided only formatting and grammatical editing changes. Tim Carlson, Research & Policy Director, performed this editorial role. For more information on the Tamarisk Coalition go to www.tamariskcoalition.org

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Executive Summary

Rivers anchor the society, economy, and ecology of the arid American West. Their stewardship is central to the region's long-term future. Restoration of rivers and riverbanks could generate many benefits, but the question remains whether increased water savings would be among them.

A panel of experts was convened in November 2008 to try to answer this question. This report focuses on ten specific questions on the current knowledge about tamarisk and Russian olive (TRO) effects on water availability. The Panel assembled to complete the report was asked to address whether TRO water use, or evapotranspiration (ET), is sufficiently understood to reasonably predict the water savings associated with TRO removal and native species restoration. The panel was also asked to detail where and how future research and demonstration projects could best contribute to tamarisk and Russian olive management and its role in the stewardship of Western rivers.

Although tasked with evaluating both tamarisk and Russian olive, the panel concluded that very little information exists about Russian olive. This report therefore addresses tamarisk almost exclusively.

Question 1: What does existing research tell us about the use of water by TRO in different ecological settings?

A key conclusion of the panel is that *native vegetation can use either more or less water than tamarisk*, depending on the identity of the native species, stand densities, and environmental and site conditions such as depth to groundwater and salinity. Panel members expressed two distinct perspectives on how ET rates can be predicted or extrapolated from one site to another: 1) ET depends on several factors that vary by site, making extrapolation relatively complex; and 2) ET is relatively well-predicted from canopy characteristics and reference ET (ET_o) for the site in question.

It is unreasonable to expect or to use a single value for ET from TRO systems. It is possible, however, to express water consumption in relatively narrow ranges for specific classes of vegetation stand characteristics and site conditions. To normalize across sites with different weather and climate, ET or water consumption measurements should not only be reported in terms of absolute units, such as mm or acre-feet, but should also be normalized for climatic evaporative demand by dividing by a reference ET (ET_o).

Question 2: Can ET measurements from lower latitude states be used to infer potential ET rates in higher latitude states? What about elevation differences?

ET rates can reasonably be re-scaled to new latitudes and elevations by expressing tamarisk ET as a fraction of reference ET (ET_oF) for each site. This would be very useful as most studies to date on ET rates have taken place in the Lower Basin states of the Colorado River.

Question 3: What is known about ET rates for replacement vegetation, both riparian and upper terrace floodplain species? What is an appropriate palette of replacement species for each ecosystem within the Colorado River watershed?

Generally speaking, ET rates for replacement vegetation are not as well studied as for tamarisk. It is clear that replacement species exhibit a very wide range of ET values, from values typically higher than tamarisk to values significantly lower. In the riparian zone phreatophytic tree communities (e.g., mainly cottonwood-willow (*Populus*-*Salix*) vegetation) which are appropriate for shallow groundwater and low salinity areas, exhibit ET rates comparable to tamarisk at maturity and full canopy closure. Some replacement species (e.g., shrubs and grasses) that have been studied exhibit lower ET rates. Replacement of tamarisk with these diverse facultative or non-phreatophytic plant types that are adapted to upper floodplain terraces may reduce ET, depending on the density of the removed tamarisk and the availability of water. However, few studies are available where tamarisk and replacement species ET were measured at the same time and place. These studies sometimes show equal or greater ET rates by possible replacement species, typically on a per-plant basis. Where replaced tamarisk stands are dense with high canopy cover, however, native replacement vegetation comprised predominately of facultative or non-phreatophytic species will seldom achieve similarly high densities or cover (and by inference, ET values) on a stand or community basis. The choice of appropriate replacement species can be based on three driving factors at nested scales: climate (regional-scale), hydrology / water table characteristics (reach-scale), and salinity (site-scale).

Salinity is a pervasive challenge in the Lower Basin, and revegetation and restoration of highly saline, xeric sites may be extremely difficult. Panel members had divergent views about the practicality, feasibility, and cost of trying to restore infested areas on such sites in the Lower Colorado River Basin. Native plant community restoration is technically achievable on many of these sites, but economic feasibility rests with value of the restored habitat as perceived or assigned by the managing agency or landowner. In comparison, several areas in the Upper Basin will likely experience passive revegetation after tamarisk control because infestations are less dense, there is good presence of native vegetation, and periodic over-bank flooding occurs.

Question 4: What role does infestation density play in overall ET rates?

ET rates for all vegetation species vary positively with amount of canopy cover for similar age class and ecological setting. It is probably sufficient to treat canopy cover categorically; i.e., high, medium, and low categories within broad size classes and types of ecological setting that can be used to assign ET rates or ranges to particular stands.

Question 5a: Can the Panel agree on a narrower range of TRO ET than is described in the literature?

Based on all available evidence, the Panel reached consensus that the typical range of tamarisk ET on western rivers is 0.7 to 1.4 meters per year, (ET_oF of 0.3 to 0.7, centering on a mean value of 0.5). The extremes of this ET range occur in distinct settings. In the southwestern US along the Colorado River, a healthy, dense tamarisk forest well supplied with groundwater can use up to 1.4 meters of water per year over a 300 day growing period (ET_oF of 0.7). A similar stand experiencing water and salinity stress, such as on upper floodplain terraces, would likely have significantly lower evapotranspiration. Insufficient knowledge exists about Russian olive to estimate its range of ET rates.

Questions 5b and 5c: Can a range of water savings per acre be agreed to? Can a relative range of water savings between TRO and replacement plant communities be agreed to?

The range of water savings is large and depends on site ecology, hydrology, and the identity of replacement vegetation. Water savings requires the replacement of tamarisk with species that require less water. This can only occur on sites appropriate for more xeric replacement vegetation.

In general, potential water savings will range from 50-60% to less than zero (if replacement vegetation uses more water than tamarisk). Water salvage will typically occur only for a few years (during early growth) in areas where riparian species such as cottonwood and willow are the appropriate replacement vegetation for tamarisk. For other replacement vegetation, potential water savings are higher but vary among species and depend strongly on site factors. The greatest opportunity for meaningful water savings will occur on upper terraces located within the floodplain. However, the greatest opportunities for recovery of other ecosystem service values may occur in the mesic riparian fringe where water savings are lower.

Question 5d: Is there potential for saving water and increasing stream flows in the Colorado River system by implementing TRO control and restoration actions?

Most panel members agreed that the potential exists for saving water and increasing stream flows in the Colorado River system, through appropriate and well-planned TRO control and restoration measures which include:

- Revegetation as a critical component of restoration.
- Replacement vegetation for tamarisk on upper floodplain terraces composed of more xeric native species suitable for site-specific precipitation, soils, salinity, and groundwater depths.
- Long-term maintenance of the restoration action.

Panel members agreed that water salvage should not be expected in areas where the appropriate replacement vegetation is willow-cottonwood and where restoration therefore necessarily revegetates with these species. Considerable areas in both the Upper and Lower Colorado River Basin (range by river reach or tributary: 20-90%) are likely suitable for restoration to species more xeric than cottonwood and willow.

More conclusive and quantitative answers to the questions of whether and how much water savings will likely occur are not yet available. Well-planned restoration experiments coupled with good ET and hydrologic monitoring and modeling would help provide a more conclusive and quantitative answer. Whether water makes it to the channel and increases surface flow or enters groundwater depends on the hydrology of the system.

Question 6: If climate change occurs, what might be the implications for ET rates from TRO as well as potential replacement vegetation? Change in range expansion?

The Panel has high confidence of a region-wide rise in temperatures throughout the year due to climate change. Temperature increases could drive higher ET by increasing the driving force for evapotranspiration and/or increasing photosynthetic rates. Increased temperatures could lead to higher ET rates by extending the growing season and regional extent of tamarisk. However, temperature, drought, and biological control stress could lower ET rates or leave them unchanged. Other factors of uncertainty include precipitation rates and forms (i.e. snow versus rain) and increased CO_2 concentrations.

Question 7: What are the implications of active biological control in the Upper Basin? Implications for the Lower Basin?

At its current rate of expansion, the tamarisk leaf beetle (*Diorhabda elongata*) will spread throughout the Upper Colorado River Basin by September 2010. The long term impact on tamarisk density remains a matter of speculation, but a 50% reduction in green tamarisk biomass seems likely across the Upper Basin within the next five years.

The northern ecotype beetles released in the Upper Basin will very likely continue to move slowly southward as they evolve to cope with southern environmental conditions. The Crete (southern ecotype) beetle population will likely make it to the Lower Basin from California. It is likely that within 5 to 10 years the beetles will be in the lower Colorado River system from either/or the Upper basin populations or the California populations. It is possible that large scale defoliations could occur soon (within 2-3 seasons) after Crete beetles reach or are introduced into the Lower Basin.

The beetles will continue to assist tamarisk control indefinitely, as they can respond to evolved resistance by the tamarisk (which herbicides cannot do). However, they need to be accompanied by active monitoring, restoration, and in some cases additional control measures to achieve desired outcomes for ET and other values.

Question 8: What are the potential benefits or impacts if TRO management within the Colorado River Basin states does not occur?

Proactive management has time and again produced better results, for lower costs, than reactive steps taken in crisis mode. It is reasonable to expect that without TRO management, both species will continue to expand – tamarisk especially in the Upper Basin, and Russian olive especially in its understory. These expansions into new areas will most likely increase ET.

The other critical point is that tamarisk management is already occurring – as described above, an effective bio-control agent for tamarisk has been released and is spreading on a regional scale within the Upper Basin. At this stage, we must consider what benefits and impacts will accrue if bio-control proceeds without any additional management measures. First, bio-control by itself will not finish the job of controlling tamarisk. Second, the chance to reclaim and restore tamarisk-invaded sites controlled by beetles is best when it is proactive rather than reactive. Finally, bio-control will reduce ET in the short term by reducing tamarisk ET. However, monitoring after bio-control will be essential for adaptive management responses such as the need to control secondary invasions.

Most of Panel members view tamarisk as a negative component of the system overall, one whose continued spread will be a detriment to the river system and whose control is desirable regardless of whether water savings can be demonstrated.

One Panel member disagrees that removing or controlling tamarisk will be beneficial or that expansion into new areas will most likely increase ET.

Question 9: Can modeling be used to clarify potential water savings resulting from TRO management?

Water savings due to TRO management can be assessed using three general modeling approaches: 1) a comparison of modeled and remotely sensed ET rates, among locations with and without TRO stands; 2) a comparison of modeled ET rates from TRO stands before and after stand removal; and 3) an integrated hydrologic model that simulates or predicts ET as a function of vegetation type, vegetation density, and climate. A hydrologic model can be used to predict if reductions in ET will be converted to groundwater storage or streamflow. These models can also indicate optimal management scenarios that maximize water savings by focusing TRO management on areas that provide the greatest benefit. A surface energy balance application has the best chance of detecting relative differences in ET rates.

Question 10: Future Research needs?

The Panel identified specific recommendations for developing quality research/demonstration sites in both the Upper and Lower Basins and the importance of establishing consistent protocols for data collection. Sites should be located on river reaches or in watersheds with well-defined boundaries, geology and surface and subsurface flows so that entire water budgets can be modeled over time. An interdisciplinary team to establish such protocols and to vet demonstration proposals should include at least one expert from each of the following areas: ecology, hydrology, remote sensing, ET modeling, direct ET measurement, restoration, and bio-control.

A number of critical issues were also identified that would greatly benefit from additional research. These include:

1. All aspects of the invasive species Russian olive;
2. Various approaches to improve ET measurement methods and to better parameterize ET models;
3. ET rates of halophytic and xeric replacement species;
4. Ecosystem response to and effectiveness of biological control;
5. Ascertain the Upper Basin’s need for active revegetation;
6. Identify the implications of TRO removal – especially on streambank erosion and stabilization; and
7. The effectiveness of soil manipulation.

In all situations, we encourage all TRO ET measurement systems and programs to receive extensive peer review by communities of experts to reduce experimental biases and pitfalls and to promote effective expenditure of public dollars.

Independent Peer Review of Tamarisk & Russian olive Evapotranspiration

Background

Over the past 50 years, tamarisk and Russian olive (TRO) have gained a reputation as aggressive invasive species that use large quantities of water. Though no known projects document water recovery following Russian olive removal, several projects have noted returning springs and wetlands and rebounding groundwater levels following tamarisk removal. Such projects are widely used to support the claim that tamarisk exploits valuable water resources. The most notable of these projects were completed at Spring Lake in Artesia, NM; Coachella Creek, CA, and Eagle Borax Springs Works, Death Valley National Park, CA (Rowlands 1990, DiTomaso 2004).

At Spring Lake, tamarisk had invaded and covered a 13-acre spring-fed lake, eliminating its surface water by 1968. Tamarisk was effectively controlled with herbicides in 1989, and by 1992 the water table had resurfaced. The Nature Conservancy Coachella Valley Preserve's tamarisk infestation had a density of approximately 80 percent. This dense stand depressed the groundwater table, suspected of decreasing the output of local springs. The stand was removed over a five year period after which oasis springs in the area rapidly recovered. At Eagle Borax Works Springs, historical records described a natural spring and associated ponds progressively drying-up as tamarisk spread began in 1950. In 1971, the park staff conducted a controlled burn of 10 acres. Eight weeks later the water table had risen 1.2 feet and a 1-acre pond had reappeared. These examples provide anecdotal evidence that tamarisk control provides water savings. As a result numerous control efforts have occurred to increase water supplies. However, few projects have produced solid scientific evidence that actual savings have occurred.

The only high quality field research of tamarisk control resulting in an increase in water supplies was performed on the Gila River upstream from San Carlos Reservoir in Arizona. The report stated

> . . . "During the first few years of the 10-year study, the natural hydrologic system was monitored using observation wells, streamflow gages, and meteorological instruments. Following this initial monitoring period, the phreatophytes were removed from the flood plain and the effects on streamflow were evaluated. The average effect of vegetation removal over the entire study reach was that the Gila River changed from a continually losing river for most years before clearing to a gaining stream during some months for most years following clearing. Specifically, average monthly values of gain or loss from the stream indicated that before clearing, the river lost water to ground water during all months for most years. After clearing, the river gained ground-water inflow during March through June and during September for most years". (Culler et al. 1982)

Although the research clearly indicated that tamarisk control lead to gains in stream flow in the Gila River, the research failed to include a revegetation component. Revegetation is essential to prevent extreme erosion or the reinvasion of non-natives such as tamarisk and Russian olive. As a result of the lack of revegetation, this study did not address the question of whether any real water savings would occur if replacement vegetation was installed.

The only other major study performed was on the Pecos River in New Mexico. This study evaluated water salvage following the removal of 18,800 acres of tamarisk from the floodplain of the Pecos River near Artesia. Tamarisk was almost entirely removed excluding some thickets on wildlife refuges and 10-m strips along each bank, left for erosion control. No discernible streamflow gain was observed. Several explanations were provided for this lack of increase in the Pecos River base flow including error in streamflow measurements, masking of salvage by variations in climate, and capture of salvaged water by groundwater pumping (Shafroth et al. 2005). Although not specifically stated in the citation, another important reason for no discernable gain in stream flow was that cleared tamarisk sites were often allowed to immediately undergo secondary encroachment by extremely dense, near 100% canopy closure, monotypic stands of kochia (*Bassia scoparia*). This is a common occurrence on many land ownerships (public and private) along the broader riparian corridors of the Pecos River in southeastern New Mexico in the absence of revegetation following tamarisk removal. This is compounded by the widespread distribution of an aggressive, high-leaf-area-index (LAI), herbicide-resistant ecotype of kochia in this locale for many years. Under this scenario, and perhaps for this reason primarily, no water salvage is likely to occur when secondary invasions fill the ecological void, with dense kochia ET (or ET from other invasives) essentially replacing tamarisk ET in the absence of natural or artificial revegetation (Lair unpublished data 2006; pers. comm. 2009).

All of these anecdotal examples and studies have led to confusion as to what might be the potential for water savings.

Purpose of the Peer Review

The purpose of the Peer review was to synthesize information on TRO evapotranspiration (ET) rates as well as those of potential replacement vegetation. The literature on TRO and native riparian vegetation describes a wide range of ET rates for each vegetation type. Partially as a result of this incongruence there is no consensus among the scientific community if a reduction in TRO will increase the availability of water resources.

Due to the wide range of reported ET rates and lack of consensus over water savings potential, it cannot currently be determined: a) how much water is being used by TRO, b) how much water could potentially be saved by controlling TRO and revegetating treated areas with native plants, and c) the cost-effectiveness of a TRO management program vis-à-vis the potential benefits.

An independent peer panel was selected as the best means of advising policy makers in the seven Colorado River Basin States (Basin States) because many experts from different fields provide a balanced understanding of the problem. The research literature typically focused on only ET rates of tamarisk and, to some extent, Russian olive. It did not evaluate riparian ecosystem structure, hydrology, and the effects of replacement vegetation. Incorporating opinions from these interrelated fields creates a balance that is critical for policy makers as it provides expert advice that sifts out biases inherent in each field of research.

The Panel's tasks were to:

1. Reach a consensus, not necessarily unanimity, on a narrower range of TRO and replacement vegetation ET rates in various ecosystems and climates, considering elevation and latitude;

2. Identify areas of additional research needs; and

3. Reach a consensus, not necessarily unanimity, of how ground water and surface water may respond to changes in vegetation over time.

The objective for the Panel was to focus the discussion of ET rates and TRO management to aid the Basin States in making informed decisions about the potential benefits and cost-effectiveness of removing TRO and restoring riparian lands.

Peer Panel Process

A peer review selection process was developed to ensure that panel members had the appropriate experience and expertise to participate, represented various aspects on the issue, had no vested interest in the outcome of the discussion, and were available. The selection process was open with key stakeholders' reviews requested to identify and approve panel members.

The Tamarisk Coalition identified a list of approximately 25 experts from its contact network and from stakeholder recommendations. These individuals were identified based on their knowledge and expertise in the areas of riparian and floodplain upper terrace ecosystems ecology; ET rate measurement of vegetation associated with these ecosystems; hydrologic interaction between vegetation, groundwater and surface water; and TRO control and revegetation approaches. Every effort was made to bring together a balanced panel with diverse experiences and opinions.

The selected panel was composed of the following ten individuals (see Appendix A for biographic sketches of each).

- Richard Allen, University of Idaho; remote sensing, ET measurement and modeling and hydrology
- Dan Bean, Colorado Department of Agriculture; biological control entomologist
- Dan Cooper, Los Alamos National Laboratory; remote sensing – LIDAR
- Ed Glenn, University of Arizona; ecophysiology and remote sensing
- David Groeneveld, Hydrobio Inc.; remote sensing
- Ken Lair, H.T. Harvey and Associates; restoration vegetation
- Christopher Neale, Utah State University; remote sensing and mapping, ET measurement and modeling
- Richard Niswonger, US Geological Survey; hydrology and modeling
- Anna Sher, University of Denver and Denver Botanic Gardens; restoration ecology
- Erika Zavaleta, University of California Santa Cruz; restoration ecology

Dr. Zavaleta served as the Chair for the panel and Tim Carlson, of the Tamarisk Coalition, served as the Panel moderator. The Panel met at the University of California Santa Cruz over a two day period dictated by the schedules of the Panel members (November 11-12, 2008). Participants from the Basin states were invited to observe the Panel's discussion. The panel sessions were audio recorded to provide the Panel backup information if necessary to develop the report. PowerPoint presentations, with audio, by each Panel member were also recorded and are provided on a Data-DVD in the back pocket of this report.

Panel Objective: *Is TRO ET sufficiently understood to reasonably predict water savings?*
The following questions for the Panel were formalized during the course of finalizing the Colorado River Basin TRO Assessment Work Plan and include input solicited from the Parties to the MOU.

1. What does existing research tell us about the use of water by TRO in different ecological settings and what information gaps require additional research?

2. Can ET measurements from lower latitude states be used to infer potential ET rates in higher latitude states? What about elevation differences?

3. What is known about ET rates for replacement vegetation, both riparian and upper terrace floodplain species? What is an appropriate palette of replacement species for each ecosystem within the Colorado River watershed?

4. What role does infestation density play in overall ET rates?

5. From answers to Questions 1 through 4:
   a. Can the Panel agree on a narrower range of TRO ET than is described in the literature?
   b. Can a range of water savings per acre be agreed to?
   c. Can a relative range of water savings between TRO and replacement plant communities be agreed to?
   d. Is there potential for saving water and increasing stream flows in the Colorado River system by implementing TRO control and restoration actions?

6. If climate change occurs, what might be the implications for ET rates from TRO as well as potential replacement vegetation? Change in range expansion?

7. What are the implications of active biological control in the Upper Basin? Implications for the Lower Basin?

8. What are the potential benefits or impacts if TRO management within the Colorado River Basin states **DOES NOT** occur? Water usage and other impacts.

9. Can modeling be used to clarify potential water savings resulting from TRO management? Are there research needs for ET values that will enhance modeling capabilities?

10. Future research needs and approaches:
    a. What field research activities and potential location(s) would be appropriate to assess potential water losses and savings associated with TRO control and revegetation? Are there well established research sites that fit the need?
    b. Should standard field and laboratory methods be established for any future ET work the Basin States may wish to undertake? If so, suggestions?
    c. What recommendation(s) can be made to calculate and measure water savings?

The Panel's charge was to use their expertise in developing a 20 to 30 page independent response to these questions. The Panel's response is presented below. The Tamarisk Coalition provided only formatting and grammatical editing changes.

As this report is a scientific evaluation of the ET issue, metric units are used predominately throughout. Conversions from metric to English units are found in Appendix D.

Consensus report:
Tamarisk and Russian olive Effects on Water Availability in The Western United States

Introduction

Rivers anchor the society, economy, and ecology of the arid American West. Their stewardship is central to the region's long-term future. Two exotic invasive tree species – tamarisk (*Tamarix* sp.) and Russian olive (*Eleagnus angustifolia*) have established along rivers throughout the Western United States. Both species have had far-reaching effects. These range from changes in river channel shape, capacity and sediment loads to displacement of native riparian forests and animals.

The most-studied, but still poorly understood, effect of tamarisk and Russian olive is on water availability itself. As stream flows and water supplies decline in the Western states, human demands for water continue to rise. Restoration of rivers and riverbanks could generate many benefits, but the question remains whether increased water savings would be among them.

The purpose of this report is to evaluate current knowledge about tamarisk and Russian olive (TRO) effects on water availability. Most existing information concerns rates of water use (evapotranspiration, ET) by TRO relative to native species displaced by them. This panel was asked to address whether TRO evapotranspiration is sufficiently understood to reasonably predict the water savings associated with TRO removal and native species restoration. The panel was also asked to detail where and how future research and demonstration projects could best contribute to our understanding of tamarisk and Russian olive management and its central role in the stewardship of Western rivers.

Although tasked with evaluating both tamarisk and Russian olive, the panel concluded that almost no information exists about Russian olive. This report therefore addresses tamarisk almost exclusively. If Russian olive management depends on a quantitative understanding of its water use and ecology, then further research on water use, invasion dynamics, and other ecological effects of this species is a priority.

Most members of this panel view tamarisk as a negative component of the system overall, one whose continued spread will be a detriment to the river system and whose control is desirable regardless of whether water savings can be demonstrated. One Panel member disagrees with this statement, especially as it relates to birds. We caution that tamarisk and Russian olive invasion must be addressed as just one component of a larger, long-term need to restore and steward Western rivers affected by many stressors. Without flood pulses and with continued incision and aggradation (sediment accumulating both in riparian vegetation and above reservoirs), these river systems will remain vulnerable to invasion, degradation, avulsion, and radical shifts in their functioning. Addressing invasive species and their impacts is necessary, but not sufficient, to sustained river restoration and functioning.

Our report is divided into ten sections that address each of the sub-questions posed to the panel.

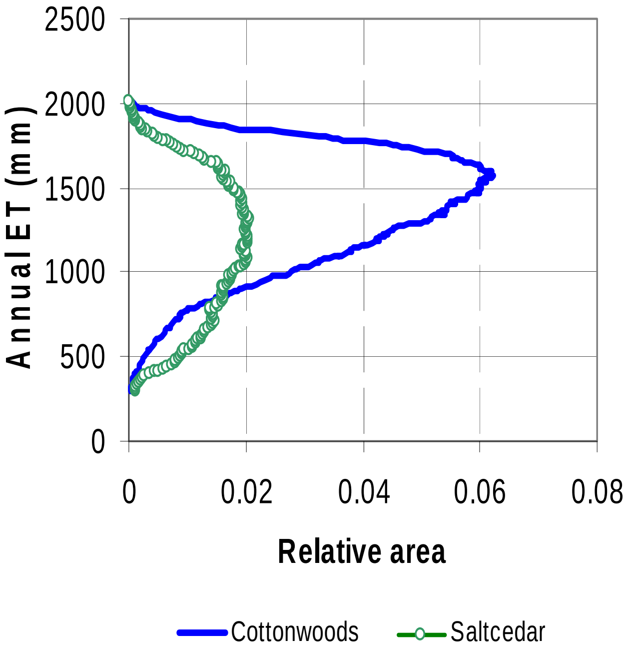
Question 1: What does existing research tell us about the use of water by TRO in different ecological settings and what information gaps require additional research?

The main purposes of this section are to describe the degree of uncertainty around ET measurements, summarize advantages and disadvantages of methods used to measure ET, and pinpoint research needs on ET by TRO. A key conclusion of the panel is that *native vegetation can use either more or less water than tamarisk*, depending on the identity of the native species, stand densities, and environmental and site conditions. Russian olive is too-little studied to draw conclusions about it at this stage. Panel members expressed two distinct perspectives on how ET rates can be predicted or extrapolated from one site to another: 1) ET depends on several factors that vary by site, making extrapolation relatively complex; and 2) ET is relatively well-predicted from canopy characteristics and reference ET (ET_o) for the site in question. We describe both.

Variation in Evapotranspiration from TRO Systems – ET rates from the same species of tamarisk or Russian olive can vary widely under the same general climatic conditions due to wide variation in vegetation density, vegetation health, height and age of the vegetation, nature of understory vegetation, and access to ground-water. Often the stand characteristics and access to ground-water vary widely with distance from a stream, soil type, shape of near stream terrain, geology and stream-ground-water interactions. Therefore, it is unreasonable to expect or to use a single value for ET from TRO systems or even a narrow range (Johns 1989). It is possible, however, to express water consumption in relatively narrow ranges for specific classes of vegetation stand characteristics. For example, old, sparse stands of tamarisk are expected to have much lower water consumption rates than densely populated five-year old stands that have ready access to ground-water. Vegetation growing in salinized soil or substantially above a water table, or that is infested with insects is expected to fall into a lower range of water consumption.

Allen et al. (2007b) sampled ET derived by satellite-based energy balance along a 150 km river corridor of the Middle Rio Grande Valley of New Mexico and derived frequency distributions of estimated seasonal ET from cottonwood and tamarisk. These frequency distributions, shown in Figure 1, exhibit wide variation in ET from both cottonwood and tamarisk. ET from tamarisk exhibited larger variance due to its tendency to grow across a wider range of water availability, water table depth, soil types, and salinity conditions, whereas cottonwoods are typically found close to stream channels.

Figure 1: Tamarisk and Cottonwood ET variation



Because ET rates from TRO vary widely, ET models have not yet been developed for these species that are readily transferred from one local area to another. Models common to agriculture and other 'uniform' systems do not transfer well to TRO because of the complex surface energy and aerodynamic characteristics and heterogeneity typical of these riparian species.

Most information and estimates of water consumption by riparian systems are therefore based on in-place measurements. These measurements show a wide range of peak and annual water consumption within each species, as described later in this report. Some of the variation in reported values is real and is caused by differences in weather (location, year) and stand characteristics such as density, age, health, and soil conditions such as salinity. Still more of the variation, however, likely results from biases or error in the measurements themselves. This bias or error can arise from the method employed, the care and quality exercised by the data collector, or the context of the measurement, where physical conditions required by the measurement system can be violated. Error can also arise from extrapolating short-term measurements (over hours, days, or weeks) to the entire growing season or year. Likely error ranges for several common ET measurement methods are summarized in Table 1. Under-reporting of methodological details in the literature means that it is not always possible to evaluate the accuracy and precision of a reported value.

Table 1: Expected error (one standard deviation) for various types of ET measurements in riparian systems (R.G. Allen, 2008 pers. comm.). Errors can be much larger if measurements are made by persons without specific expertise in the method and underlying theory used.

Method	Typical error relative to actual ET, %	Typical additional error caused by equipment and operator malfunction, %
Lysimeter	5-15	5-40
Container studies	20-100	
Soil water balance	10-30	10-40
Bowen ratio	10-20	5-40
Eddy Covariance	15-40	10-40
Remote Sensing energy balance	10-20	10-30
Remote Sensing using vegetation indices	15-40	10-20
Sap Flow	15-40	20-100
Scintillometers	10-35	5-30

Evapotranspiration Measurement – Methods include soil water balance, lysimeters, eddy covariance, Bowen Ratio, remote sensing, scintillometry and sap flow. Inherent to all of these methods is the reality that an improperly designed experiment or measurement can lead to highly erroneous estimated water use (Anderson and Idso 1985). As the result, estimates of water savings from water salvage projects are often optimistic (Johns 1989). Many, but not all, panel members felt that in general, values from tank/container studies should not be used in developing ET estimates.

Comparing and extrapolating across sites – To normalize across sites with different weather and climate, ET or water consumption measurements should not only be reported in terms of absolute units, such as mm or acre-feet, but should also be normalized by dividing by a reference ET (ET_o) to create the "fraction of reference ET", ET_oF. This is because ET demand is a strong function of weather and climate. ET rates can change by a factor of five or more day to day as weather changes. For the same month, average ET can change by as much as 20% from year to year due to differences in weather systems. Annual ET for the same location can change by as much as 15 to 20% for the same reasons. Because ET is an energy-governed process, ET demands generally decrease with increased elevation and latitude and increase with the regional dryness. For example, annual ET demands in western Colorado may be only one-half to two-thirds that for the Palo Verde area of California.

Reference ET, ET_o, is a standardized representation of climatic evaporative demand at a given site. ET by a particular species such as tamarisk, when expressed as a fraction of reference ET, or an ET_oF, are more transferrable across locations and weather. The ET_oF is equivalent to the commonly used 'crop coefficient' and effectively describes the physiological and local physical characteristics (such as water availability or stand density) that impact the ET rate while the ET_o describes the impact of weather and climate on the consumptive rate[1].

Research gaps identified by the panel:

- More studies of Russian olive ET are needed. This species may call for a sap flow approach, which is measured at the scale of individual trees, because RO does not occur in the big, continuous stands necessary for most other measurement techniques.

- ET estimates would be improved by study of the relationship between canopy density and ET rates, and stand age and ET rates, for both TRO and natives.

- Similarly, ET estimates would be improved by study of how to better extrapolate and apply reference ET to riparian areas, with their lower temperatures, wind speed and higher humidity than surrounding areas more typically addressed by this type of extrapolation.

- The effects of the current bio-control agent, the tamarisk leaf beetle *Diorhabda elongata* (see Question 7), on vegetation, the course of succession, and the time course of change in ET need to be better understood.

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[1] ET_o is best calculated using the ASCE-EWRI (2005) standardization of the Penman-Monteith equation if dependable data for solar radiation, wind speed, air temperature and humidity are available. If these data are not available, then a more simple but dependable method such as Hargreaves and Samani (1985) is recommended. **Use of a stand density function to estimate ET_oF:** Vegetation density functions have been used to predict expected values for ET_oF as a function of stand appearance and characteristics. A basic model for this is given in the FAO-56 publication on evapotranspiration (Allen et al. 1998). Refinements of the method are described in ASABE (2007). Similar methods should be explored for riparian systems to provide more narrowed ranges of expected water consumption. These vegetation-characteristic based methods can be combined with ground-water elevation models, precipitation and ET_o models to produce more accurate estimates of water consumption.

- In order to compare TRO ET rates to ET rates by halophytic (salt-tolerant) and xeric (drought-tolerant) native species, more studies of ET rates by the latter are needed.

- A greater range, and number, of study sites for ET of TRO and native vegetation, is lacking, especially in the Upper Basin.

- In the Upper Basin, more research is needed on whether and where active revegetation will be an important component of successful restoration of TRO invaded sites.

- While we know that ET rates decline under water stress, research is needed on plant stomatal behavior under water stress conditions (high temperature, drought) and how it affects 24-hour estimates of ET.

- Energy balance methods, such as Bowen ratio and eddy correlation, rely strongly on assumptions about vertical vapor and heat transfer over stands. However, advection (horizontal air movement) is inevitable. To accurately measure ET, further research is needed on how to account for advection and on how it influences dynamics at different types of sites.

- The implications of TRO removal (by bio-control and other methods) for various processes, including sediment movement, wildlife habitat (endangered fishes, birds) and succession, require greater study.

- Scaling up ET measured for small samples or sampled areas to represent ET from larger areas

- Scaling up transpiration measured by sap flow to ET that includes evaporation from soil and intercepted precipitation as well as transpiration from understory vegetation.

Question 2: Can ET measurements from lower latitude states be used to infer potential ET rates in higher latitude states? What about elevation differences?

Most studies to date on ET rates have taken place in the Lower Basin states of the Colorado River. The full latitudinal range of TRO is therefore not well-represented by current ET studies. This should be addressed by future ET studies, as should the possibility that other tamarisk species besides *T. ramossissima* (the most-studied one) could have different ET dynamics. In the meantime, ET rates can reasonably be re-scaled to new latitudes and elevations by expressing tamarisk ET as a fraction of reference ET (ET_oF) for each site (see Question 1). We estimate that error from this approach can be within 10-20% of ET rates measured on-site, provided that differences between sites in water availability and precipitation patterns are taken into account.

Question 3: What is known about ET rates for replacement vegetation, both riparian and upper terrace floodplain species? What is an appropriate palette of replacement species for each ecosystem within the Colorado River watershed?

Riparian restoration and prevention of re-invasion both require the promotion of replacement vegetation following TRO removal. Replacement vegetation is also critical for bank stabilization and erosion control, wildlife habitat enhancement, forage production for wildlife and livestock, recreation, aesthetics, and other ecosystem services. Replacement species need to be selected foremost for suitability to target sites, since without their successful establishment none of these goals will necessarily be met. However, characteristics such as their effects on ET and wildlife habitat may also guide their selection.

Generally speaking, ET rates for replacement vegetation are not as well studied as for tamarisk, particularly for facultative or non-phreatophytic species that tend to dominate plant composition on upper floodplain terraces. There are very few data for herbaceous cover species other than selected sacaton grasses (*Sporobolus* spp.) and inland saltgrass (*Distichlis spicata*). It is clear that replacement species exhibit a very wide range of ET values, from values typically higher than tamarisk to values significantly lower (Table 2).

In the riparian zone phreatophytic tree communities, mainly cottonwood-willow (*Populus-Salix*) vegetation typical of former floodplains in Western river systems, exhibit ET rates comparable to tamarisk at maturity and full canopy closure. Many other replacement species (e.g., shrubs and grasses) that have been studied exhibit lower ET rates. In the mesic riparian fringe, phreatophytic trees are likely an appropriate revegetation choice for both site suitability and the recovery of habitat, aesthetic and other values associated with this zone. There may be a period of several (5-15) years following cottonwood /willow planting when their ET rate, although increasing as they mature, is still significantly less per unit land area than the tamarisk stands they replaced. In some cases this may not hold true as in older more decadent tamarisk stands, which may use less water than younger more vigorous stands.

Tamarisk also invades well beyond the mesic riparian fringe; upper floodplain terraces comprise the vast bulk of tamarisk-infested area. Arid- to xeric-adapted shrubs and grasses are appropriate choices for replacement species in this zone. Replacement of tamarisk with diverse facultative or non-phreatophytic native vegetation that is adapted to upper floodplain terraces (with their deeper water tables and/or higher soil salinity) may reduce ET. Although studies were conducted under different site conditions, these native species and plant community associations exhibit ET values ranging roughly from 50-75% of mean tamarisk stand values often cited in the literature (Table 2).

The choice of appropriate replacement species can be based on three driving factors at nested scales – climate (regional-scale), hydrology/ water table characteristics (reach-scale), and salinity (site-scale). Examples of candidate revegetation species recommended for use in riparian restoration in the Colorado River Basin, rated according to hydrologic regime and salinity tolerance, are described Shafroth et al. (2008). Appropriate replacement species could also depend on whether target sites are on free-flowing or regulated river reaches. Appendix B provides recommendations for restoration of replacement vegetation following tamarisk control or removal. (Note: A more complete list of replacement vegetation for different ecosystems within the Colorado River Basin is being compiled for the main body of the Assessment Report).

The Upper Colorado River Basin contains tamarisk at elevations up to 9,000 feet (though it is mapped only up to 6,500 feet). In the Upper Basin, replacement vegetation differs between two principal substrates: Colorado Plateau sandstones (with native vegetation such as bunchgrasses and shrubs), and marine shales (with native vegetation such as salt-tolerant alkali sacaton, saltgrass, saltbush, and greasewoods). In the Lower Colorado River Basin, replacement vegetation outside of the mesic riparian zone (which typically supports cottonwood/willow and associated species) typically includes a range of xeric-adapted and salt-tolerant shrubs, grasses, and forbs. Salinity is a pervasive challenge in the Lower Basin for revegetation. As a result restoration of these highly saline, xeric sites may be extremely difficult. Panel members had divergent views about the practicality, feasibility, and cost of trying to restore infested areas on such sites in the Lower Colorado Basin. Native plant community restoration is technically achievable on many of these sites, but economic feasibility rests with value of the restored habitat as perceived or assigned by the managing agency or landowner. In comparison, several areas in the Upper Basin will likely experience passive revegetation after tamarisk control because infestations are less dense, there is good presence of native vegetation, and periodic over-bank flooding occurs.

Research gaps identified by the panel:

- Further research on ET is needed, particularly to characterize the effects of stand density and age on TRO ET, xeric and salt-tolerant species, mixed-species communities, and young cottonwood stands with herbaceous understories.

- Because streambank erosion and stabilization can be a concern following tamarisk removal, research is needed on phased approaches to control and revegetation that maintain stable vegetative protection and bank armoring over time.

- Research is needed on the utility of retaining young tamarisk as nurse habitat for planted native species in mixed stands. Anecdotal evidence suggests that younger, mixed stands of tamarisk and native species provide moisture and/or shading conditions conducive to the establishment and early survival of seeded natives.

- Development and application of revegetation strategies need to keep pace with technological developments in tamarisk biological control.

- On xeric sites with dense, mature, monotypic infestations, revegetation is difficult without soil manipulation to prepare a seedbed and restore soil processes (Taylor et al. 1999, Pinkney 1992, Szaro 1989, Horton and Campbell 1974, Hogan 2003, Lair and Wynn 2002, NRC 2002). Research is needed to assess effectiveness of techniques to achieve this, including tamarisk litter dispersal or incorporation, improved seed contact with mineral soil, reduced surface salinity, mycorrhizal inoculation, and nitrogen manipulation.

Table 2: Daily and/or annual evapotranspiration (ET) estimates for native, non-phreatophytic vegetation types (individual species and plant community associations) occurring in upper terrace floodplain sites, western United States (adapted from Shafroth et al. 2005, with additions.

Veg Type	**ET**[1] ***mm*** d^{-1} (***m*** yr^{-1}) [***ac-ft*** yr^{-1}]	**Study Location**	**Method**	**Citation**
Mesquite (*Prosopis* spp.)	(0.4)	San Pedro River, AZ	BR	Scott et al. 2000
	1.6 – 2.4	San Pedro River, AZ	BR	Scott et al. 2000
	(0.6 – 0.7)	San Pedro River, AZ	EC	Scott et al. 2004
	(1.02)	Arizona	??	Gatewood et al. 1950
	[2.1-2.3]	San Pedro River, AZ	EC/BR	Scott et al. 2006
Honey mesquite (*Prosopis glandulosa / P. juliflora*)	(0.47)	Lower Colorado River (near Blythe, CA)	BR	Wiesenborn 1995
	[2.9]	Acme-Artesia area, NM	??	USBR 1979
Velvet mesquite (*Prosopis velutina*) woodland	(0.64-0.69) ++	San Pedro River, AZ	SF / EC	Leenhouts et al. 2006
Velvet mesquite shrubland	(0.57) ++	San Pedro River, AZ	SF / EC	Leenhouts et al. 2006
Mixed saltcedar / Honey mesquite	(1.0)	Lower Colorado River (near Blythe, CA)	BR	Wiesenborn 1995
Mixed saltcedar / Screwbean mesquite (*Prosopis pubescens*)	(0.37)	Lower Colorado River (near Blythe, CA)	BR	Wiesenborn 1995
Savannah woodland: velvet mesquite / big sacaton mixed stand	3.5	Tucson, AZ	EC	Yepez et al. 2003
Arrowweed (*Pluchea sarothroides*)	(0.37)	Lower Colorado River (near Blythe, CA)	BR	Wiesenborn 1995
Quailbush (*Atriplex lentiformis*)	(0.69)	Lower Colorado River (near Blythe, CA)	BR	Wiesenborn 1995

Veg Type	**ET [1]** ***mm d^{-1} (m yr^{-1}) [ac-ft yr^{-1}]***	**Study Location**	**Method[2]**	**Citation**
Inland saltgrass	(0.3 - 1.2)	Various sites	LYS	Weeks et al. 1987
(*Distichlis spicata*)	1.1 – 4.5	Sonora, NM	LYS	Miyamoto et al. 1996
Inland saltgrass	(0.45 – 1.15)	Owens Valley, CA	LYS	Young and Blaney 1942
	(0.4 – 0.9)	Santa Ana, CA	LYS	Young and Blaney 1942
	(0.25 – 1.25)	Los Griegos, NM	LYS	Young and Blaney 1942
Inland saltgrass / alkali sacaton	[1.2]	Acme-Artesia area, NM	??	USBR 1979
Big sacaton	0.3 – 1.6	San Pedro River, AZ	BR	Scott et al. 2000
(*Sporobolus wrightii*)	(0.55) ++	San Pedro River, AZ	SF / EC	Leenhouts et al. 2006
	[1.8]	San Pedro River, AZ	EC/BR	Scott et al. 2006
	50% of mesquite shrubland site; 25% of cottonwood site	San Pedro River, AZ	SF / EC??	Qi et al. 1998
Alkali sacaton / desert seepweed	(1.05 – 1.2)	Carlsbad, NM	LYS	Blaney and Hanson 1965
(*Suaeda suffrutescens*)	(0.57 – 0.67)	Artesia & Bitter Lakes NWR, NM	BR	Weeks et al. 1987
	(0.40)	Artesia & Bitter Lakes NWR, NM	EC	Weeks et al. 1987
"Grassland" (saltgrass / alkali sacaton??)	[0-1.99]	Los Lunas, NM	??	USACE/USBR 2002

[1] Values without parentheses or brackets are reported in mm d^{-1} units; values within parentheses are reported in (m yr^{-1}) units; values within brackets are reported in [ac-ft yr^{-1}] units.

[2] Methods include Bowen Ratio (BR), Eddy Covariance (EC), Sap Flow (SF), and Lysimeter (LYS)

"??" symbol indicates that it was unclear what the specific ET measurement technique or plant species was

++ Growing season only.

Question 4: What role does infestation density play in overall ET rates?

ET rates vary positively with canopy cover for similar age class and ecological setting. Many existing studies do not report canopy cover. However, it is probably sufficient to treat canopy cover categorically; i.e., high, medium, and low categories used to assign ET rates or ranges to particular stands. One study, at the Cibola National Wildlife Refuge, explicitly compared three nearby stands of different canopy cover and found that ET ranged from 0.55 to 0.88 to 1.34 m/year in low, medium, and high canopy stands, respectively (Christopher Neale 2008, pers. comm.).

On tamarisk stands that have reached higher canopy cover, with near-monotypic or full monotypic composition and full canopy closure (the Middle Rio Grande, Pecos, and Lower Colorado being prime examples), age class will make a definite difference, yielding a wide spectrum of ET rates within the same canopy cover class. This is especially true as plants lose vigor under deeper water table conditions (i.e., drought). Two scenarios illustrate this specifically:

1. A young, monotypic tamarisk stand with higher green foliage:woody stem biomass ratio (often maintained by high fire frequency) will exhibit higher ET rates than an old, decadent, monotypic stand (undisturbed for decades) that is 95%+ woody biomass - with both states exhibiting 100% canopy closure.

2. Similarly, a young and active, but patchy or mixed tamarisk stand with relatively low plant (or stem) density may still have higher ET rates than an older, decadent, monotypic stand with higher densities and full canopy closure.

Question 5a: Can the Panel agree on a narrower range of TRO ET than is described in the literature?

Tamarisk evapotranspiration varies depending on many interacting factors, such as climate; canopy cover, age, and health; water table depth; water quality and salinity. Based on all available evidence, the Panel assembled by the Tamarisk Coalition reached consensus that the typical range of tamarisk ET on western rivers is 0.7 to 1.4 meters per year, (ET_oF of 0.3 to 0.7, centering on a mean value of 0.5). Actual area-wide ET rates might be lower than this average, as most of the flux tower studies were set in denser stands to provide homogeneous measurement conditions. Insufficient knowledge exists about Russian olive to estimate its range of ET rates.

Table 3 provides literature values of ET measured in natural stands of tamarisk on western U.S. rivers based on flux tower, sap flow and remote sensing methods. These studies represent the range of values that can be expected for typical dense stands. Values ranged from 0.6 to 1.45 meters per year, with a mean value of 0.94 meters per year. Inclusion of studies based on other methods (but excluding tank studies, as discussed in Question 1) yields a slightly higher mean ET value for tamarisk of 1.0-1.1 m/yr[2].

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[2] Sample size of 49 studies if all years are included, and of 35 studies if only studies conducted since 1985 are included.

Table 3: Estimates of wide-area tamarisk ET from selected studies involving different river systems, measurement techniques and water table and cover conditions.

Location	ET (m/yr)	Method	References
Havasu NWR, Colorado River, AZ/CA	0.8	Bowen Ratio Flux Towers	Westenburg et al. 2006
Middle Rio Grande, NM	0.8 – 1.2	Eddy Covariance Flux Towers	Cleverly et al. 2002, 2006
Dolores River, UT	0.6 – 0.7	MODIS EVI/T_a	Dennison et al. 2008
Colorado River Delta, Mexico	1.1	MODIS EVI/ T_a	Nagler et al. 2007
Virgin River, NV	0.75 – 1.45	Bowen Ratio Flux Tower	Devitt et al. 1998
Cibola NWR, Colorado River, AZ	1.15	Sap Flow and MODIS EVI/ T_a	Nagler et al. 2008
Pecos and Rio Grande Rivers, TX	0.75	Sap Flow	Owens and Moore 2007
Bosque del Apache NWR, Rio Grande River, NM	1.0	Eddy Covariance Flux Towers	Hattori 2004
Mean	**0.94**		

The extremes of this ET range occur in distinct settings. In the southwestern US along the Colorado River, a healthy, dense[3] tamarisk forest well supplied with groundwater can use up to 1.4 meters of water per year over a 300 day growing period, suggesting an ET_oF of 0.7. A similar stand experiencing water and salinity stress, such as on upper floodplain terraces, would likely have significantly lower evapotranspiration (Hattori 2004). Similarly, lower stand densities result in lower ET rates.

Recent measurements of ET using Bowen Ratio systems at the Cibola Refuge (unpublished) by the US Bureau of Reclamation have shown a wide variation of tamarisk ET within the same area and illustrate how variation in stand canopy cover, water table depth, soil properties, and salinity levels interact to influence ET[4]. The implication is that remote sensing, which is typically based on stand canopy cover along with reference ET, will provide a good estimate of the upper limit of ET over a broad area for a particular stand but not of actual or average ET on a plant basis.

Finally, tamarisk often occurs in mixed stands with other species such as cottonwood and Russian olive (e.g., Cleverly et al., 2002, 2006), such as in the upper reaches of the Colorado River system with narrow riparian zones in canyons. Based on the similar ET rates observed for tamarisk and mesic riparian tree species (see Question 3) and the consistency of ET rates across mixed stands

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[3] with green leaf area index (LAI) values of 4 or above

[4] The annual average ET_oF values varied between 0.3 (peak ET of 2.5 mm/day, 0.54 m/year) for a location 1.5 km away from the river with a green LAI of around 2 and high salinity level in the ground water, to 0.7 (peak ET of 7.5 mm/day, 1.3 m/year) at a location 750 meters from the river with average salinity levels and similar water depths to the first site but with green LAI values of 4. A third site only 200 meters from the Colorado River presented a measured annual ET_oF value of 0.45 with average peak ET in the summer of 5 mm/day and a total seasonal ET of 0.87 m/year. This latter site had the best water quality, lowest depth to the water table, but a stand density resulting in a green LAI of 2.6.

with varying tamarisk cover (Nagler et al. 2005)[5], these mixed stands typically would have ET rates within the middle range of monotypic tamarisk stands.

Questions 5b and 5c: Can a range of water savings per acre be agreed to? Can a relative range of water savings between TRO and replacement plant communities be agreed to?

The range of water savings (or loss) is large and depends on site ecology, hydrology, and the identity of replacement vegetation. Potential water savings depends upon the replacement of tamarisk with species that require less water. As described in Question 3, this can only occur on sites appropriate for more xeric replacement vegetation. The selection of replacement vegetation should also take into account other desired values such as wildfire management and wildlife habitat.

In general, potential water savings will range from 50-60% to less than zero (if replacement vegetation uses more water than tamarisk). Water salvage will typically occur only for a few years (during early growth) in areas where riparian species such as cottonwood and willow are the appropriate replacement vegetation for tamarisk. Cottonwoods and willows (CW) typically have ET similar to tamarisk[6]. For other replacement vegetation besides CW, potential water savings are higher but vary among species and depend strongly on site factors. Across many studies conducted since 1985 (and excluding tank studies as per the panel's recommendation in Question 1), ET by xeric replacement species such as saltgrass and other xeric-adapted herbs and shrubs averaged 0.5 m/yr (45%) lower than ET by tamarisk (Zavaleta et al. in review).

The greatest opportunity for meaningful water savings will thus be on upper terraces located within the floodplain away from the river, where the water table is deep, the replacement native species more xeric in character, and reduced opportunity exists for reestablishment of TRO due to reduced frequency or absence of recurrent overbank flooding. However, the greatest opportunities for recovery of other ecosystem service values may occur in the mesic riparian fringe where water savings are lower.

Finally, the structure and composition of replacement vegetation communities will not be entirely under the control of managers and will vary over time – planted species can decline and/or other species can possibly colonize over time. It is therefore important to consider ET associated with a range of communities that could come to inhabit the site.

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[5] Nagler et al. (2005) compared wide-area ET rates on the Upper San Pedro, Middle Rio Grande and Lower Colorado Rivers using flux tower and remote sensing data and found that riparian vegetation used about 0.8 to 0.9 meters per year on all three rivers, despite differing from < 5% to > 80% in Tamarisk cover.

[6] Consensus estimate for CW: 0.9-1.4 m/yr [ET_oF = 0.45-0.7]; consensus estimate for tamarisk 0.7-1.4 m/yr [ET_oF =0.3-0.7]. CW rates do not range as low as tamarisk because CW cannot colonize more xeric, upper floodplain terrace sites that tamarisk can. However, rates as low as 0.6 m/yr have been observed for stressed CW stands.

Question 5d: Is there potential for saving water and increasing stream flows in the Colorado River system by implementing TRO control and restoration actions?

Most panel members agreed that the potential exists for saving water and increasing stream flows in the Colorado River system, through appropriate and well-planned TRO control and restoration measures which include:

- Revegetation as a critical component of restoration.
- Replacement vegetation for tamarisk on upper floodplain terraces composed of more xeric native species suitable for site-specific precipitation, soils, salinity, and groundwater depths.
- Long-term maintenance of the restoration action.

Panel members agreed that water salvage should not be expected in areas where the appropriate replacement vegetation is willow-cottonwood and where restoration therefore necessarily revegetates with these species. Considerable areas in both the Upper and Lower Colorado River Basin (range by river reach or tributary: 20-90%) are likely suitable for restoration to species more xeric than cottonwood and willow.

More conclusive and quantitative answers to the questions of whether and how much water savings will likely occur are not yet available. Well-planned restoration experiments coupled with good ET and hydrologic monitoring and modeling would help provide a more conclusive and quantitative answer. As of now, we have no direct, long-term, before-after studies of tamarisk removal and restoration to the point of mature native/replacement vegetation to conclusively answer this question. The best we have are a few before/after studies that detected short-term reductions in ET or increases in surface water, but these do no not address the long-term course of water recovery as replacement vegetation matures.

Whether water makes it to the channel and increases surface flow or enters groundwater depends on the hydrology of the system. Ground-based measurement, aerial extrapolation, and modeling would help identify where recovered water will go on a reach-by-reach basis. In losing reaches, water recovered from tamarisk will likely go to groundwater stores rather than surface flows and will not be measured as in-stream increases. Hydrologic conductivity also must be sufficient for the salvaged water to enter the channel. Because river systems tend to have very coarse-textured sediments, hydrologic conductivities are almost always sufficient to permit this.

Reaches can be assessed as gaining or losing by a number of methods, including ground-based measurement of the water table gradient away from the channel, ground-based measurement of rates of upward or downward water flux through the channel bottom, and aerial photography to extrapolate from point measurements on the ground. Where a reach is gaining, the water table rises (i.e., has a higher elevation) away from the channel. In gaining reaches the riparian corridor tends to be much wider with gradation from vigorous vegetation at the channel margins to lower and lower vegetation away from the channel. By contrast, in losing reaches the water table and the phreatophyte riparian vegetation that depend on it can both tend to decline relatively quickly with lateral distance from the channel. These generalities are, of course, subject to local terrain and geology.

Any increases in Colorado River Basin flow due to salvage will be difficult to measure even if they are considerable. Even on gaining reaches, potential water salvage is often a small part of the entire river discharge, would mainly occur during the summer when plants use water, and will be difficult to measure because of large natural variation in flows and stream gage accuracy. Warming trends and climate variability among years will also contribute background noise against which long-term water recovery must be measured. Modeling and remote sensing approaches, described more in Question 9, can help overcome these challenges on a reach-by-reach basis.

Question 6: If climate change occurs, what might be the implications for ET rates from TRO as well as potential replacement vegetation? Change in range expansion?

Climate change is already occurring. It includes changes in a range of factors including temperature; storm intensity; and precipitation amount, frequency, seasonality and form. We have high confidence of a region-wide rise in temperatures throughout the year, but predictions of precipitation changes vary widely. We also have high confidence of declining regional snowpack driven by temperature increases, which results in higher winter and lower summer flows and water availability. These two conditions, temperature change and precipitation change, associated with climate change are considered below.

Temperature changes – We focus here on how increased temperatures and reduced winter snowpack could affect ET rates, TRO ranges, and water availability. In addition, we briefly consider the potential effects of rising atmospheric carbon dioxide concentrations, which have already increased substantially (~30%) over baseline levels.

The panel agrees that ET rates by both TRO and native species (except as noted) could respond to temperature increases via several pathways:

- Temperature increases could drive higher ET by increasing the driving force for evapotranspiration and/or increasing photosynthetic rates.

- Temperature increases could increase ET rates by extending the growing season, defined as the period when plants have active leaves. Leaf development in spring and leaf drop in fall are temperature-mediated phenomena (in concert with photoperiod). Growing season lengths are extending globally and have already lengthened by 1-2 weeks in various temperate regions (Menzel 2000, Schwartz and Reiter 2000). Tamarisk is active year-round in Mexico (no delimited growing season); this feature could extend north into US, also increasing tamarisk ET rates.

- Climate change will increase the regional extent of tamarisk, especially in the Upper Basin. Higher temperatures will allow tamarisk to expand upwards in elevation, and possibly in latitude. To the moister north, competition from other plants might limit expansion. An expanded distribution increases the area over which ET differences between tamarisk and native vegetation would affect water availability.

- On the other hand, plant water and temperature stress exacerbated by warming could lead to earlier daily stomatal closure by leaves, leading to net unchanged or lower ET rates than under current and recent temperatures. This deserves further study.

- Temperature interacts with the bio-control agents (beetles) currently used to defoliate tamarisk in parts of the West. At higher temperatures, the bio-control beetle could be more active and effective, reducing ET and extent of tamarisk. The beetles will emerge earlier if tamarisk puts out leaves earlier in spring. The bio-control beetles, currently limited to more northerly parts of the invaded region but gradually expanding south, may be able to accelerate this expansion at higher temperatures. This is because the minimum day length requirement that currently keeps them north relaxes at higher temperatures.

- Increases in ambient temperature and atmospheric CO_2 will also produce varying impacts on the characteristics and degree of native plant community competition in terms of differential effects on the primary photosynthetic pathways of plants (i.e., C_3 vs. C_4). In general, higher temperatures should provide ecophysiological advantage (e.g., water use efficiency, drought tolerance, biomass allocation and productivity, resilience to herbivory, etc.) to warm-season (C_4) species. This would potentially increase native competition to re-invasion by tamarisk or other secondary invasive species by the predominant native plant component (C_4) in southwestern desert ecosystems. Conversely, increases in atmospheric CO_2 may provide similar advantage to cool-season (C_3) species, whose photosynthetic pathways facilitate incorporation of increased levels of CO_2 much more readily and at higher maximum saturation rates within leaf tissue than C_4 plants. This derived advantage may not compensate, however, for the comparatively reduced or minority composition (i.e., frequency, density, cover, biomass) and thus community-level competitiveness of cool-season species or populations in desert ecosystems.

- Overall herbivory, by other animals, could increase or change as well, though the direction and nature of change is difficult to anticipate.

The panel also agrees that temperature-driven changes in snowpack and water availability could affect riparian ET rates in the following ways:

- In snow-dominated systems, water availability could drop in summer, so ET might not change because ET rates are limited by water availability.

- Increasing CO_2 concentrations could reduce ET by increasing plant water use efficiency and reducing stomatal conductance. This response has been observed in a wide range of, but not all, plant species exposed to increased CO_2 concentrations.

- If reservoir levels drop, fringes will likely be invaded by tamarisk, increasing its extent locally.

Precipitation changes – While changes in precipitation will vary within the region, we know that ET reflects water availability. In places and at times when precipitation increases and leads to higher moisture availability to plants, we expect ET rates to increase. In places and at times when precipitation goes down and produces reduced moisture availability to plants, we expect ET rates to go down. These changes would interact with the direct effects of temperature on ET rates described above.

We also expect that increasing storm intensity will alter river morphology in at least some parts of the region to produce more erosion, gullies, and sediment movement. In such areas, the capacity of bank vegetation to hold sediment could become more important to bank and channel stabilization. Finally, new sediment aggradation above reservoirs resulting from a storm-driven increase in the rate of sediment transport could create new tamarisk habitats and increase its extent.

The physiological change described above in response to temperature, reduced soil moisture, and increased CO_2 could apply equally to both native and exotic vegetation. The net effects of these changes on the difference between TRO and replacement vegetation could therefore be small or none.

Question 7: What are the implications of active biological control in the Upper Basin? Implications for the Lower basin?

Background – The first open releases of the tamarisk leaf beetle, *Diorhabda elongata*, in North America were made in 2001 at 7 experimental sites in 6 western states. By 2006 four of these sites, located near Lovell, WY, Delta, UT, Schurz, NV and Lovelock, NV, had each experienced at least 2,000-hectare defoliations. Beetle populations at the Lovelock site have now expanded to periodically defoliate an estimated 30,000 hectares of tamarisk in and around the Humboldt Basin in northwestern Nevada. Observations made at these sites help assess potential impacts of the leaf beetles on tamarisk in the Colorado River watershed. At latitudes lower than 36°-20’N (approximately 75 km below the southern border of Utah and Colorado) there are no days long enough to stimulate beetle reproduction, so beetles will have only a single generation per year (Bean et al. 2009). To overcome this limitation, southern adapted *D. elongata* populations were imported from the island of Crete and have been successful in the south (Texas) and in the coast range of California (Carruthers et al. 2006). In eight years since the open release of the beetle there have been no reports of damage to non-target plant species.

Tamarisk plants are notoriously resilient, but the beetle eventually killed a portion of the tamarisk population at all four experimental sites. The beetles feed on tamarisk plants at all stages of growth, from seedlings and resprouts to mature trees. Overall mortality from the four field trial sites range from 10-80%. Tamarisk plants growing under poor conditions, such as in dry areas with deeper water tables, are more susceptible to beetle-induced mortality. It is now known that tamarisk death by beetles is a slow process, requiring at least 6 defoliations and three growing seasons; and that mortality is never complete within a tamarisk stand. Defoliation by beetles is therefore not likely to reduce ET substantially for the first 1-2 years. After that, impacts on ET will depend on what vegetation colonizes the site.

Upper Basin implications – At its current rate of expansion, the beetle will spread throughout the Upper Colorado River Basin where tamarisk is growing by September 2010. The long term impact on tamarisk density remains a matter of speculation, but a 50% reduction in green tamarisk biomass seems likely across the Upper Colorado River Basin within the next five years. Tamarisk leaf beetles were first introduced into the Upper Colorado Basin in 2004 by Grand County, UT weed managers along the Colorado River near the town of Moab, UT. By the end of 2008 beetles had moved into most of southwestern Colorado and southeastern Utah and had defoliated 8,000 or more hectares of tamarisk along the Colorado, Green, San Rafael, and Dolores Rivers and their tributaries. Beetles were also released in Dinosaur National Monument, on the Green River, near the confluence with the Yampa, in 2006. By 2008 large but unquantified areas of tamarisk lining the Green and Yampa Rivers were defoliated.

Lower Basin implications – There have been no tamarisk biological control agents introduced into the Lower Basin by the USDA; however, northern beetles moved from the Delta, UT experimental site by Utah weed managers are now well established in the Virgin River drainage and have moved south out of Utah and into northern Arizona (Dudley 2009). They will likely continue to move slowly southward as they evolve to cope with southern environmental conditions. It is reasonable to assume that they won't reach the lower Colorado River for at least another five years, although they may not adapt at all. The Crete (southern) beetle population; however, will likely make it to the Lower Colorado River from California. It is possible that large scale defoliations could occur soon (2-3 seasons) after Crete beetles reach or are introduced into the Lower Basin.

The beetles will continue to assist tamarisk control indefinitely, as they can respond to evolved resistance by the tamarisk (which herbicides cannot do). However, they need to be accompanied by active monitoring, restoration, and in some cases additional control measures to achieve desired outcomes for ET and other values. Population dynamics and impacts on tamarisk stands need to be closely followed in long-range studies. Other effects such as the impacts of high beetle densities on predators need to be known. Finally, the opening of tamarisk canopies will allow regrowth of native plants, but restoration will likely be required in many settings to prevent exotic re-invasion and ensure revegetation.

Figure 2: Defoliated tamarisk (brown) and native vegetation (green), 2008.

Monitoring of the Colorado River in 2008 (see Figure 2) between Lake Powell and Grand Junction provided indications that native plant communities are rebounding. These include such plants as coyote willow (*Salix exigual*), bunch grasses, rabbitbrush (*Chrysothamnus nauseosa*), fourwing saltbush (*Atriplex canescens*), and skunkbush (*Rhus trilobata*). Noxious weeds such as Russian knapweed (*Acroptilon repens*), whitetop (*Cardaria draba*), and perennial pepperweed (*Lepidium latifolium*) were also found. (Tamarisk Coalition 2008)

Question 8: What are the potential benefits or impacts if TRO management within the Colorado River Basin states does not occur?

Proactive management has time and again produced better results, for lower costs, than reactive steps taken in crisis mode. It is reasonable to expect that without TRO management, both species will continue to expand – tamarisk especially in the Upper Basin, and Russian olive especially in its understory. Because ecosystems are dynamic and always changing, we cannot forecast how rapidly spread will occur in the future or what other surprises might arise. However, continued expansion into new areas will most likely increase ET. Continued expansion will also heighten already-growing concerns about fire, because tamarisk fuels fires kill native cottonwood and willow forests. Continued expansion will likely produce further negative effects on federally listed upriver fishes because of infilling of critical backwater habitat. Proactive management of these exotic species and of the river and riparian ecosystems they affect is necessary to address not only water salvage but also biodiversity conservation, the stability of river beds and banks, and many other values. One Panel member disagrees that removing or controlling tamarisk will be beneficial even if there is no water savings. Recent research on the Lower Colorado River shows that birds do use tamarisk and that when it is cleared, habitat value decreases (Hinojosa-Huerta 2006, van Riper 2008, Sogge et al. 2008).

The other critical point is that TRO management has already occurred – as described above, an effective bio-control agent for tamarisk has been released and is spreading on a regional scale within the Upper Basin. At this stage, we must consider what benefits and impacts will accrue if bio-control proceeds without any additional management measures. First, bio-control by itself will not finish the job of controlling tamarisk. Without follow-up action, areas where tamarisk has been defoliated by the bio-control agent may experience reinvasion, resprouting, and new invasions. Second, the chance to reclaim and restore tamarisk-invaded sites controlled by beetles is best when it is proactive rather than reactive. Active revegetation of these sites could save water in the end because it would allow managers to direct or accelerate re-establishment and successional trajectories of competitive native plant communities, rather than allowing equally competitive invasive species to colonize these sites. Finally, bio-control will reduce ET in the short term by reducing tamarisk ET. However, monitoring after bio-control will be essential for adaptive management responses such as detection of the need to move in and control secondary invasions.

Question 9: Can modeling and remote sensing be used to clarify potential water savings resulting from TRO management? Are there research needs for ET values that will enhance modeling capabilities?

Water savings due to TRO management can be assessed using three general modeling approaches: 1) a comparison of measured and remotely sensed ET rates, among locations with and without TRO stands; 2) a comparison of modeled ET rates from TRO stands before and after stand removal; and

3) an integrated hydrologic model that simulates or predicts ET as a function of vegetation type, vegetation density, and climate. These approaches have relative advantages and disadvantages, and their success depends on selection of study areas that meet necessary requirements for estimating ET and other hydrologic variables. All three of these approaches require models in the form of equations used to estimate ET from data measured at flux towers; equations used to extrapolate local ET estimates to regional scales using remotely sensed data (Allen et al. 2007ab, Groeneveld and Baugh 2007); and equations used to estimate ET with water balance methods within a region encompassing a local flow system (Tóth 1962, Markstrom et al. 2008).

A promising approach for estimating water savings resulting from TRO management is to compare ET estimates among locations dominated by TRO stands to locations that are either sparsely vegetated or else are dominated by other types of vegetation. Measurements of transpiration and evaporation using flux towers, soil water content probes, and soil-core analysis play an important role in this approach because they are required to confirm estimates from remote sensing and models. Point-scale ET estimates can be extrapolated to regional estimates using remotely sensed surface temperatures and/or vegetation index distributions (Allen et al. 2007ab, Groeneveld and Baugh 2007). Success for measurements using flux towers and, in some cases, remote sensing requires study areas that have extensive areas of uniform TRO stands, for example more than 200 m on a side. Remote sensing methods, especially those employing surface energy balance, are effective for determining ET from areas that are sparsely vegetated or vegetated with more xeric species. An important requirement with both ET measurements and models is to normalize results using ET_o to produce ET_oF because potential ET is not equivalent among comparative areas. For example, differences in ET among areas could be indicative of contrasts in water and energy availability, soil texture, and geology rather than vegetation type and density. Systems measuring individual plants, such as sap flow, lysimeters and soil measurement systems, require large numbers of samples to obtain representative values for the total population and, in the case of sap flow, require means to estimate evaporation from soil and rainfall intercepted by the canopy.

The second approach uses models or remote sensing to compare estimates of ET rates from TRO stands before and after stand removal, and is likely the most accurate method if it can be done correctly. However, this method may not be feasible due to the length of time required to establish baseline ET estimates before TRO removal, and the length of time required to establish a quasi-steady state following the succession of new stands of vegetation. As in the first approach, physical or remote sensing models generally require measurement of ET from flux towers or other systems to verify the model before extrapolating estimates to encompass large areas of dense TRO stands (Groeneveld and Baugh 2007). However, as indicated by Table 1, ET measurement systems are prone to a host of random and systematic error, including error by the operators. Therefore, validation or invalidation of physical and remote sensing models by point measurements is often not conclusive. The second approach would benefit from making measurements of streamflow and groundwater heads in the vicinity of the experimental area to determine if estimated water savings are corroborated by increased stream baseflow and groundwater storage.

The third method uses models to estimate hydrologic response to changes in vegetation type and density. This method has the advantage of being flexible: it does not require the first method’s comparative landscapes or the second method’s long monitoring period before and after TRO removal. Another advantage is more predictive information about changes in water availability following TRO management. A hydrologic model can be used to predict if reductions in ET will be converted to groundwater storage or streamflow. These models can also indicate optimal management scenarios that maximize water savings by focusing TRO management on areas that provide the greatest benefit. Because models such as GSFLOW can provide predictions of hydrologic response, many future scenarios can be considered to account for uncertainties in future climatic conditions and management options[7].

We stress that hydrologic models can be the most uncertain and inaccurate tool for estimating water savings from TRO management if these models are not properly developed, calibrated, tested or constrained. However, a substantial benefit of hydrological modeling is that models can constrain ET estimates according to the whole hydrologic flow system, including groundwater storage and streamflow. Furthermore, rather than only estimating water savings due to TRO management, hydrologic models can predict how water savings may change in response to changes in climate and in water management, such as changes in withdrawals, diversions or impoundment. Finally, hydrologic models can help identify sensitivity to key variables that affect water savings, such as soil texture, proximity to surface water, and land surface and groundwater altitude.

Question 10a: What field research activities and potential location(s) would be appropriate to assess potential water losses and savings associated with TRO control and revegetation? Are there well established research sites that fit the need?

For future research, a representative suite of sites should be considered that builds on existing research and can test long-standing questions about restoration potential in TRO-invaded sites. To represent the full range of situations in which TRO occur, study sites should include those with a range of:

- Canopy densities
- Potential native vegetation types
- Elevations
- Locations in both the Upper and Lower Basins
- Presence and absence of bio-control insects and defoliation
- Groundwater depths
- Degrees of difficulty to achieve restoration / restoration potential
- Salinities
- Hydrologic conditions (free-flowing and controlled reaches with and without flooding)

Sites should also be located on river reaches or in watersheds with well-defined boundaries, geology and surface and subsurface flows so that entire water budgets can be modeled over time[8]. Ideally, sites would be selected in pairs and established as paired control and restoration sites to provide

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[7] More work is required to link integrated hydrologic models such as GSFLOW to remotely sensed estimates of ET over large regions. Remotely sensed estimates of ET could be used to parameterize models used to calculate actual ET based on reference ET, vegetation characteristics and water availability.

[8] A number of specific hydrological issues need to be addressed before any site is included, such as whether significant deep percolation is likely and whether the reach is gaining or losing.

more accurate information about the effects of TRO removal on water savings and other ecosystem services. A scientific task group could identify sites that meet the above criteria.

The panel recommended the inclusion of certain study designs to address long-standing questions about TRO removal, restoration, and water savings.

- In the Upper Colorado River Basin, the panel recommends studies that use remotely sensed estimates of ET to compare areas actively and passively revegetated following beetle defoliation or other TRO removal methods. Remotely sensed estimates allow inclusion of sites within narrow canyons and with other topography that limits use of flux towers or other micrometeorological ET approaches.

- In the Lower Colorado River Basin, the panel recommends the inclusion of a high-salinity, xeric site or sites to test whether restoration is possible under these circumstances.

- In parts of one or more sites, it would be useful to follow the effects on ET of cutting tamarisk and then allowing it to regrow. We know little about the effects of tamarisk regrowth and regrowth rates on ET through time.

- In parts of one or more sites, it would also be useful to test or demonstrate staged tamarisk control and revegetation in a way that maintains and improves habitat throughout the project. This type of restoration approach will be particularly critical in areas where tamarisk currently supports wildlife of concern, such as the southwestern willow flycatcher.

- At one or more sites, we recommend study or demonstration of potential economic / beneficial uses of harvested tamarisk biomass.

- In at least some sites with active bio-control beetles, we recommend study of how the bio-control process interacts with other control measures such as herbicide spraying and cutting; how active revegetation can best be initiated while tamarisk is declining; and how the beetles affect resprouting and resprouts.

Question 10b and 10c: Should standard field and laboratory methods be established for any future ET work the Basin States may wish to undertake? If so, suggestions.
What recommendation(s) can be made to calculate and measure water savings?

ET measurements need to be comparable across sites. To achieve this, the panel stresses that it is more important that multiple methods be used to estimate ET at each site than that the same methods be used at each site. The best measurement approaches depend on site characteristics, but ideally every site would involve at least one direct method of measuring ET such as flux towers (micrometeorological approaches), sap flow, or isotope tracer methods. We note that micrometeorological approaches are inappropriate for canyon areas and for narrow stands of riparian vegetation; and that sap flow may be the preferred direct approach for Russian olive at all sites since it generally occurs in mixed stands.

In all situations, we encourage all TRO ET measurement systems and programs to receive extensive peer review by communities of experts to reduce experimental biases and pitfalls and to promote effective expenditure of public dollars.

Biological changes, such as biodiversity responses and plant succession, need to be carefully monitored consistently across sites. We stress the importance of establishing consistent protocols for data collection at the outset of an integrated research program. An interdisciplinary team to establish such protocols and to vet demonstration proposals should include at least one expert from each of the following areas: ecology, hydrology, remote sensing, direct ET measurement, restoration, and bio-control. This team should ensure that methods across a range of variables are comparable and mutually compatible and that all proposed sites are compatible with all identified measurement needs. This team can also guide initial site evaluation for appropriate hydrological characteristics.

Finally, we recommend that data collection at sites start as soon as possible as the first of three research phases. First, to accurately gauge the effects of restoration and other treatments, multiple years of data should be collected before the treatments are implemented at study sites. This phase includes basic site characterization – automated weather stations should be installed as soon as possible at all sites, and their hydrology characterized (e.g. surface flux, control volumes). Second, when treatments are initiated, they should begin at only one of each pair of study sites so that they can be compared to a control site for multiple years. Finally, if treatments are effective based on comparisons with before-treatment data (within sites) and with control sites (within years), then treatment can be fine-tuned and applied to the sites that served as controls.

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Appendix A
Biographic Sketches of Peer Panel Members and Moderator

Panel Members

Panel Chair: Erika S. Zavaleta Ph.D.

Education

Ph.D. Biological Sciences, Stanford University, 2001.
A.M. Anthropology, Stanford University, 1995.
A.B. Anthropology, Stanford University, 1992.

Current Position

2003-present Assistant Professor, Environmental Studies Dept., UC Santa Cruz

Research Expertise

Dr. Zavaleta is a community and ecosystem ecologist whose work focuses on the consequences of changing biological diversity and the link between ecological condition and human well-being. Dr. Zavaleta's work strives to bridge ecological theory and research to sound conservation and management practice. To that end, her research incorporates collaboration with conservation practitioners and elements of economics, public policy, and anthropology.

Richard Glen Allen, Ph.D., P.E.

Education

Ph.D. Civil Engineering, University Idaho, 1984
M.S. Agricultural Engineering, University of Idaho, 1977
B.S. Agricultural Engineering, Iowa State University, 1974

Current Positions

Professor of Civil Engineering and Biological and Agricultural Engineering, December 1998 to Present. University of Idaho.

Member, Landsat Science Team, National Aeronautics and Space Administration and U.S. Geological Survey, 2006-2011.

Research Expertise

Dr. Allen is an expert on measurement of evapotranspiration and prediction using Landsat satellite imagery and SEBAL (Surface Energy Balance Algorithm for Land) and related theory. He has studied regional advection effects on evapotranspiration using lysimetry, Bowen ratio and eddy covariance techniques. He has a background in estimation of hydrologic components. He was part of the American Society of Civil Engineers Committee on Evapotranspiration in Irrigation and Hydrology that developed standardized methods for computing evapotranspiration.

Dan Bean, Ph.D.

Education

Ph.D.	Entomology, Zoology minor, University of Wisconsin, Madison, 1983.
M.S.	Entomology, University of Wisconsin, Madison, 1978.
B.A.	Biology, University of California, Santa Cruz, 1975.

Current Positions

2005-present State Biological Control Specialist, Director, Palisade Insectary, Biological Pest Control Program, Colorado Department of Agriculture,

Affiliate Faculty, Dept. Bioagricultural Sciences and Pest Management, Colorado State University, Ft. Collins

Research Expertise

Dr. Bean is an entomologist who has studied diapause in agricultural pests for over twenty years. He currently works on biocontrol insects for the Colorado Department of Agriculture and is an expert on bio-control of Tamarisk using the Tamarisk leaf beetle *Diorhabda elongata*. Dr. Bean identified the importance of the control of diapause in determining the range of *D. elongata* and has also published on monitoring techniques for this species. In addition, Dr. Bean also studies biocontrol of two other relevant invasive species: Russian knapweed and Russian olive.

Dan Cooper, Ph.D.

Education

Ph.D. Watershed Management, The University of Arizona, 1990.
M.S. Soil Genesis and Morphology, Pennsylvania State University, 1986.
B.A. Environmental Science, Hunter College, City University of New York, 1980.

Current Position

2005 to present Staff Scientist, Systems Lead-Angelfire, Los Alamos National Laboratory.

Research Expertise

Dr. Cooper has extensive experience with remote sensing of vapors, specifically the use of LIDAR (Light Detection and Ranging). He has conducted research on surface/atmosphere interactions using micrometerological point instrumentation, LIDAR and other remote sensing techniques. Dr. Cooper was the principal investigator for the Raman water vapor LIDAR that was used to study spatial processes in boundary layer physics. He was also the chief scientist for the GEONET program, an initiative for a multinational, multidisciplinary program to understand and address environmental issues using the expertise of weapons scientists and engineers.

Ed Glenn, Ph.D.

Education

Ph.D. Botanical Sciences, University of Hawaii, 1978
M.S. Botanical Sciences, University of Hawaii, 1973
B.A. Biology, University of Hawaii, 1969

Current Position

Professor, Soil, Water & Environmental Science, University of Arizona
Joint Appointment, Professor, Wildlife & Fisheries Science, University of Arizona

Research Expertise

Dr. Glenn is an expert in phytoremediation and revegetation whose research encompasses evapotranspiration and ecohydrology of riparian vegetation, specifically that of tamarisk and native vegetation. Dr. Glenn uses remotely sensed vegetation indices, canopy attributes and plant physiological processes to inform ecological restoration and water management. His work integrates remote sensing techniques, such as MODIS (Moderate Resolution Imaging Spectroradiometer) and SAVI (Soil Adjusted Vegetation Index), with ground techniques, such as sap flow, to estimate evapotranspiration.

David Groeneveld, Ph.D.

Education

Ph.D. Dissertation: Nevada saltbush (Atriplex torreyi) autecology in relation to
phreatic versus xeric habitats. Colorado State University 1985.
M.A. Environmental Biology, University of Colorado 1977.
B.A. Environmental Biology, University of Colorado 1975.

Current Position

President, HydroBio

Research Expertise

Dr. Groeneveld's 30-plus-year career has focused on the ecology, hydrology and management of rangeland, riparian and shallow groundwater habitats for clients that included private, federal, local and state agencies across the American Southwest. His extensive professional experience has emphasized remote sensing and spatial analysis for water management. Dr. Groeneveld holds the Ecological Society of America's highest certification, that of Certified Senior Ecologist. He is also a commercial pilot with over 4400 hours of pilot-in-command flight time.

Ken Lair, Ph.D.

Education

Ph.D. Rangeland Ecosystem Science, Colorado State Univ., Fort Collins, 1998
M.S. Rangeland Ecosystem Science, Colorado State Univ., Fort Collins, 1979
B.S. Biology/Zoology, Harding Univ., 1972

Current Position

Associate Restoration Ecologist, H.T. Harvey and Associates

Research Expertise

Dr. Lair's expertise includes upland and riparian revegetation planning, technology, research and land treatment; invasive species ecology, weed treatment technology, and integrated weed management planning and application; mycorrhizal applications in revegetation; and coordinated resource management planning. Most recently, Dr. Lair spent over 7 years with the Bureau of Reclamation (BOR), serving as national research leader and project manager for various revegetation research projects, including saltcedar (*Tamarix* spp.) control and restoration of infested sites to native riparian plant communities in several western states.

Christopher M. U. Neale, Ph.D.

Education

Ph.D. Agricultural Engineering, Colorado State University, 1987.
M.S. Agricultural Engineering, Colorado State University, 1983.
Civil Engineering Degree, Escola de Engenharia Mauá, Sao Paulo, Brazil 1980.

Current Position

Professor, Utah State University

Research Expertise

Dr. Neale has over 23 years of experience in applied remote sensing. He has developed a low-cost airborne remote sensing system that has been recently used to map spatially distributed energy balance terms and evaporates of riparian and agricultural vegetation. Dr. Neale's research interests include energy balance and evapotranspiration over natural and agricultural ecosystems, mapping and monitoring of streams and riparian systems and wetland delineation.

Richard Niswonger, Ph.D.

Education

Ph.D. Hydrologic Sciences University of California, Davis 2006.
M.S. Hydrogeology, University of Nevada, Reno 2001.
B.S. Environmental Engineering Humboldt State University 1997.

Current Position

Research Hydrologist, Project Chief

Research Expertise

Dr. Niswonger's current work focuses on developing an integrated surface-water and groundwater interactions model. This project uses new and existing theoretical approaches for simulating all aspects of the hydrologic cycle within watershed and ground-water basins. This work involves developing governing equations, solution methods and programming code that can be used by the scientific community to solve water resources problems. The main product of this project is the integrated model called GSFLOW and the associated documentation and training courses.

Anna A. Sher, Ph.D.

Education

Ph.D. Biological Sciences, University of New Mexico, 1998.
B.A. Biology and Art, Earlham College, 1991.

Current Positions

Associate Professor, University of Denver
Director of Research, Herbaria and Records, Denver Botanic Gardens

Research Expertise

Dr. Sher is a plant ecologist with a particular interest in conservation issues and expertise in ecology and restoration of *Tamarix* invasions. Her lab has conducted the first multi-state surveys of re-vegetated restoration sites, using multivariate statistical tools to identify environmental variables (such as soil salinity, precipitation level, temperature, etc.) associated with restoration success. In addition, her research investigates how controlling invasive species influences plant communities.

Tim Carlson, P.E.

Education

M.S. Environmental Engineering, Arizona State University, 1975.
B.S. Civil Engineering, Arizona State University, 1972.

Current Position

Executive Director, Tamarisk Coalition

Research Expertise

Mr. Carlson has more than 35 years of experience in the environmental field working in the private sector with various cities, states, Federal agencies, and with various non-profit organizations. During this period he has facilitated several high level peer reviews for national laboratories and federal agencies on complex environmental problems. One career achievement of note is his work with the Department of Energy and State Department developing environmental research opportunities for displaced scientists at the end of the Cold War. Mr. Carlson is also a member of the Invasive Species Advisory Council to the National Invasive Species Council.

Appendix B
Recommendations for Restoration of Replacement Vegetation Following Tamarisk Control or Removal

Concepts Related to Riparian Vegetation Establishment, Soil Salinity, and Hydrologic Regime – A Restoration Practitioner Approach

Moist to Mesic Sites

On sites where favorable soils, climate and hydrology prevail, potential for natural recovery or artificial restoration of native species and associated desirable wildlife habitat is greatly enhanced. These sites (true riparian zones) closely correlate with hydrologic (shallow groundwater; $\leq$ 2m), hydrographic (frequent seasonal river overbank flows), and soil salinity (electrical conductivities [EC's] less than 4) regimes necessary to promote and sustain establishment of (as examples) native, phreatophytic cottonwoods (*Populus* spp.) and/or willows (*Salix* spp.) (Anderson 1995, Jackson et al. 1990). Supplemental irrigation can often compensate for the absence of one or more of these abiotic processes, particularly in terms of fulfilling plant water demand and for dilution or leaching of salts from the soil rhizosphere. However, in most applications, irrigation in lieu of natural hydrologic processes is not sustainable or cost-effective in the long-term.

Numerous studies have demonstrated successful approaches in selection of plant materials (phreatophytic and non-phreatophytic species); seeding or planting techniques; correlation with hydrologic, hydrographic and climatic regimes; and successional establishment strategies (Luken 1997) leading to sustainable native plant communities ***on riparian sites exhibiting these favorable environmental conditions*** (e.g., Taylor and McDaniel 2004, 2001, DeLoach et al. 2000, McCown 2000, Taylor et al. 1999, Briggs 1996, Wiesenborn 1995, Pinkney 1992, NRCS 1985, NMWPRS 1979, Horton and Campbell 1974, Merkel and Currier 1971). To the extent that riparian sites approach or exhibit the favorable environmental characteristics previously described for soil and water resources, establishment of mesic native species (adapted trees, shrubs, forbs and grasses) in lower (moist to mesic) floodplain zones can be successfully accomplished with a high degree of confidence, within the context of sound assessment of site potential and strategic planning.

Arid to Xeric Sites

More distal zones of the historic floodplain (from the active river channel) occupied by longer-term tamarisk infestations are typically comprised of upper terraces exhibiting deeper water tables (> 2m), higher soil salinity (EC $\geq$ 4), and flood frequencies often exceeding 5 years. This zone corresponds to the hydrologic, hydrographic, and salinity regimes that typically support arid to xeric upland vegetation commonly characterized by facultative or non-phreatophytic shrub / forb / grass associations (Anderson 1995, DeLoach et al. 2000). As such, this complex of environmental constraints is difficult to overcome or ameliorate in natural plant community recovery or anthropogenic revegetation measures following tamarisk control. Presence of dense standing dead or defoliated tamarisk biomass following non-mechanical control measures poses limitations in relation to seeding techniques, seed interception in aerial applications, and shading impacts. Undisturbed soil surfaces impacted by tamarisk leaf exudates and senescent litter accumulation, inherently high soil salinity/sodicity under extremely xeric climatic regimes, hummocky microrelief, nitrogen limitations, and possible recreational or livestock trampling compaction restrict potential for successful revegetation. Absence of arbuscular mycorrhizae specifically symbiotic to native revegetation species (especially grasses and shrubs), because of the long duration of tamarisk occupation in dense, mature stands, may also be a significant constraint.

Despite these constraints, numerous studies have also addressed revegetation in more arid riparian locales, demonstrating variable degrees of establishment success. Comprehensive reviews of many of these individual studies are found in Bay and Sher (2008), Lair and Wynn (2002), Pinkney (1992), and NMWPRS (1979). Several of these studies are located in riparian (historic floodplain) tamarisk infestation sites along the Colorado River, with primary research objectives addressing establishment of native plant communities on sites where potential is limited for natural or artificial recovery of willow and/or cottonwood species because of unavailability of supplemental water (via seasonal flooding, shallow water table, or irrigation).

Consistent through the bulk of these is use of dryland-adapted, highly salt-tolerant native species. These species characterize essentially salt-desert shrub/forb communities that include as dominants, shrub genera such as saltbush (*Atriplex* spp.), mesquite (*Prosopis* spp.), acacia (*Acacia* spp.), wolfberry (*Lycium* spp.), seepweed (*Suaeda* spp.), seep willow (*Baccharis* spp.), desert willow (*Chilopsis* spp.), iodinebush (*Allenrolfia* spp.), and alkali goldenbush (*Isocoma* spp.). Common forbs as sub-dominant understory genera include salt heliotrope (*Heliotropium* spp.), globemallow (*Sphaeralcea* spp.), and evening primrose (*Oenothera* spp.).

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Appendix C
Acronyms & Initialisms

ASABE	American Society of Agricultural and Biological Engineers
ASCE-EWRI	American Society of Civil Engineers, Environmental & Water Resources Institute
BR	Bowen Ratio
CW	Cottonwood and willow
EC	Electrical conductivity
ET	Evapotranspiration
ET_o	Reference evapotranspiration or Reference crop evapotranspiration
ET_oF	Fraction of reference evapotranspiration
EVI/Ta	Enhanced Vegetative Index/Temperature air
FAO	Food and Agriculture Organization of the United Nations
GSFLOW	Coupled Ground-water and Surface-water FLOW model by USGS
LAI	Leaf area index
LYS	Lysimeter
MOU	Memorandum of Understanding
MODIS	Moderate Resolution Spectroradiometer
NWR	National Wildlife Refuge
SF	Sap flow
TRO	Tamarisk and Russian olive

Appendix D
Metric units to English units Conversion Table

Metric Unit	English Unit
meter (m), 1,000 millimeters (mm)	39.37 inches, 3.28 feet
hectare	2.47 acres
kilometer (km), 1,000 meters	0.62 miles, 3,280 feet

Appendix E
Definitions

Advection – The horizontal component in the transfer of air properties. For example, the heat and water vapor content of the air at the earth's surface varies appreciably and by the wind systems these properties are transferred to other areas (Stiegeler 1976).

Aerodynamic – *Aerodynamic Roughness:* An index of the nature of airflow near the ground surface (or in this case the vegetative canopy). A surface is aerodynamically smooth if there is a layer of air immediately above it that has laminar flow. However, in meteorological terms, nearly all surfaces are aerodynamically rough, producing turbulent flow down to the ground surface, even for the lightest winds (Stiegeler 1976).

Aggradation – The sediment accumulating both in riparian vegetation and above reservoirs.

Arid – Term used to describe a climate or habitat having a low annual rainfall of less than 250 mm with evaporation exceeding precipitation and a sparse vegetation (Lincoln et. al 1998).

Avulsion – Lateral displacement of a stream from its main channel into a new course across its floodplain. Normally it is a result of the instability caused by channel aggradation (the general accumulation of unconsolidated sediments on a surface which thereby raises its level) (Allaby and Allaby 1991).

Bowen ratio (or energy budget) – Calculates evaporation as latent heat from the surface energy budget using the ratio of sensible to latent heat (Bowen ratio) derived from the ratio between atmospheric temperature and humidity gradients measured a few meters above vegetation (Shuttleworth 2008).

Container studies – Container studies refer to that category of studies that have grown vegetation in small containers that have often been too small to include representative amounts of soil evaporation or have often been placed in unnatural environments and elevated above the natural soil surface so that radiative and aerodynamic characteristics are unrepresentative of a natural environment (Allen et al. 1998, pers. comm. 2009).

Crop coefficient – The calculated value of a given crop's ET that, when multiplied by a reference crop's evaporation (ET_o) in similar climactic conditions, estimates that crop's evapotranspiration rate (Woodhouse 2008). One of the most basic crop coefficients (K_c) is the ratio of the ET observed for the crop studied to that observed for the reference crop under the same climactic conditions (Allen et. al 1998).

Defoliate – To shed leaves; to lose leaves; to cause a tree to lose its leaves (Durrenberger 1973).

Degradation –The diminution of biological productivity or diversity (Gregorich et al. 2001).

Demonstration project – Large-scale TRO restoration projects identified in Public Law 109-320 that will serve as research platforms to address critical TRO management issues. These issues include water savings, impacts to habitat and biodiversity, economics, etc.

Eddy covariance (also called eddy correlation) – Calculates evaporation as 20- to 60-minute time averages from the correlation coefficient between fluctuations in vertical windspeed and atmospheric humidity measured at high frequency (~10Hz) at the same location, a few meters above vegetation (Shuttleworth 2008).

Evaporative demand – The requirement for the air to be capable of absorbing moisture. An index of this is the saturation deficit, which is the difference between the saturation vapor pressure and actually vapor pressure. If the saturation deficit is large, as in warm dry air, the gradient between the moist surface and the atmosphere will be high and so the rate of transfer will be large. With moist air the humidity gradient will be less and the rate of evaporation correspondingly smaller (Stiegeler 1976).

Evapotranspiration – The combined system of vapor transfer by evaporation and transpiration from the ground surface and its vegetative layer (Stiegler 1976).

Exotic – A plant or animal species that is not indigenous to a region; intentionally or accidentally introduced and often persisting (Peale 1996).

Gaining stream –Streams which receive groundwater. Water table is further above the elevation of the stream's surface as distance from stream increases (Peale 1996).

Halophytic – *Halophyte:* A plant living in saline conditions; a plant tolerating or thriving in an alkaline soil rich in sodium and calcium salts (Lincoln et al. 1998).

Herbaceous – *Herb:* A plant having stems that are not secondarily thickened and lignified (non-woody and which die down annually (Lincoln et al. 1998).

Herbivory – A form of predation in which an organism, usually an animal, consumes an autotroph, usually a plant.

Heterogeneity – *Heterogeneous*: Having a non-uniform structure or composition (Lincoln et. al 1998).

Incision – The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley; esp. the downcutting of a stream, during, and as a result of, rejuvenation, whether due to relative movement (uplift) of the crust or to other cause. Also, the product of such a process e.g. an incised notch or meander (Roberts and Jackson 1980).

Invasive species – Legally, invasive species are defined as an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health (Executive Order 13112). Ecologically, they are introduced species that can thrive in areas beyond their natural range of dispersal. These plants are characteristically adaptable, aggressive, and have a high reproductive capacity. Their vigor combined with a lack of natural enemies often leads to outbreak populations (Plants...[updated 2009]). The *Invasive Species Definition and Clarification White Paper* (http://www.invasivespeciesinfo.gov/docs/council/isacdef.pdf) developed by the Invasive Species Advisory Committee to the National Invasive Species Council provides excellent detail on the implications of invasive species.

Leaf area index – Leaf area index or LAI is the total one-sided area of leaf tissue per unit ground area.

Litter dispersal – The loss of litter or recently fallen plant material which is only partially decomposed and in which the organs of the plant are still discernible, forming a surface layer on some soils (Lincoln et al. 1998).

Losing stream – A stream in which water is being lost to the groundwater system. Ground water is deeper below stream surface as distance from stream increases (Peale 1996).

Lower Colorado River Basin - The Colorado River Watershed beginning at Lee's Ferry just below Glen Canyon Dam and terminating in the Gulf of California. The Lower Basin covers portions of Arizona, California, Mexico, Nevada, New Mexico, and Utah.

Lysimeter – The process of estimating ET by measuring the change in weight of an isolated, preferably undisturbed soil sample with overlying vegetation (if present) while measuring precipitation to and drainage from the sample plot (Shuttleworth 2008). Lysimeters are special containers that are placed at ground level in natural settings and where the container should be large enough to contain representative amounts of evaporation from soil and transpiration from vegetation. ET is determined from lysimeters by monitoring the change in weight of the lysimeter or by noting the change in water table elevation (Allen et al. 1998, pers. comm. 2009).

Mesic – Applied to an environment that is neither extremely wet (hydric) nor extremely dry (xeric) (Allaby and Allaby 1991).

Mesic riparian fringe – The transition zone between fully riparian and fully mesic vegetation communities.

Model – A mathematical formulation intended to represent a natural phenomenon or system; a system of postulates, data and inferences presented as a mathematical description of an entity or state (Lincoln et al. 1998).

Mycorrhizal inoculation – The introduction of fungus that is associated in a symbiotic relationship with the root system of a plant (Durrenberger 1973).

Nitrogen manipulation – The use of nitrogen for the benefit of restoration. Nitrogen is the most abundant gas in the atmosphere and a critical constituent in the soil, which can only be used directly by a few specialized bacteria. To be of widespread value it has to be converted into the nitrate form. In nature nitrogen is involved in cyclic changes termed the Nitrogen Cycle which is basically a change from animal life to nitrites to nitrates to plant life to animal life (Stiegeler 1976).

Non-phreatophytic – A non-phreatophytic plant does not habitually obtain its water supply from the zone of saturation; a hydrophyte (plant growing in wet conditions), mesophyte (plant growing in medium conditions), or xerophyte (plant growing in dry or desert conditions) (Durrenberger 1973).

Photosynthetic rates – The rate at which photosynthesis occurs. Photosynthesis is the biochemical process that utilizes radiant energy from sunlight to synthesize carbohydrates from carbon dioxide and water in the presence of chlorophyll (Lincoln et al. 1998).

Phreatophyte (obligate and facultative) – A phreatophyte is a plant that habitually obtains its water supply from the zone of saturation either directly or through the capillary fringe (Durrenberger 1973). Obligate phreatophytes require access to groundwater at all times and life stages whereas facultative phreatophytes access it for only a portion of their water requirements or life stages.

Plant stomatal behavior – The actions of the stomata of leaves that control the loss of water vapor, or stomatal transpiration. Contributing factors include stomatal resistance and conductance. Stomatal resistence is the property of the stomata in restricting the free exchange of carbon dioxide (CO_2) by a plant leaf; the major constraint on CO_2 uptake into the plant leaf, governed largely by the diameter of the stomatal pores. Stomatal conductance is the reciprocal of stomata resistance (Lincoln et al. 1998).

Reference ET - An estimate of what evapotranspiration would be over a highly studied reference vegetation, that is, well-watered and actively transpiring grass of a certain height. Reference ET is [often] calculated using the Penman-Monteith equation, and expresses the energy available to evaporate water and the wind available to transport water vapor from the ground into the air, for the reference vegetation type (Woodhouse 2008).

Remote sensing estimates using energy balance – evaporation is deduced indirectly from the surface energy balance, with sensible heat calculated from the difference between air temperature and the temperature of the evaporating surface, along with an estimate of the aerodynamic exchange resistance between these two (Shuttleworth 2008).

Remote sensing using vegetation indices – Remote sensing using airborne or satellite sensors (e.g., Moderate-resolution Imaging Spectroadiometer or MODIS) to measure vegetation characteristics through NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index) (Measuring Vegetation (NDVI&EVI)…[updated 2009]).

Restoration – The process of returning a site from a disturbed or totally altered condition to a previously existing natural or altered condition. This process requires some knowledge of the type of wetland that existed prior to modification (Peale 1996).

Rhizosphere – The narrow region of soil surrounding plant roots that is directly influenced by root secretions and associated soil microorganisms.

Riparian zone – Riparian zones are the interfaces between terrestrial and aquatic ecosystems. As ecotones, they encompass sharp gradients of environmental factors, ecological processes, and plant communities. Riparian zones are not easily delineated but are composed of mosaics of landforms, communities, and environments within the larger landscape. The importance of riparian zones far exceeds their minor proportion of the landscape base. Interactions between terrestrial and aquatic ecosystems include modification of microclimate (e.g., light, temperature, and humidity), alteration of nutrient inputs from hill slopes, contribution of organic matter to streams and floodplains, and retention of inputs (Gregory et al. 1991). Riparian lands are defined by EPA simply as areas adjacent to streams, rivers, lakes, and freshwater estuaries. BLM defines it as lands along, adjacent to, or contiguous with perennially or intermittently flowing rivers and streams, glacial potholes, and shores of lakes and reservoirs with stable water levels. Excluded are such sites as ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil (Colorado DNR 1998).

Salinity – Occurs as either the total dissolved solids (TDS) (Peale 1996) in water or as salts and minerals in the soil available to soil moisture for dissolution. As the salinity of soil water around a plant’s root system increases, greater osmotic pressure is required on the part of the plant to extract water molecules from the soil (Hem 1967). When a plant cannot generate enough osmotic pressure to separate water molecules from salt and other dissolved solids, it will succumb to drought stress and desiccation.

Sap flow – The measure of plant transpiration by measuring the rate of sap flow in trunk, branches, or roots using heat as a tracer, with an estimate of the area of wood through which flow occurs (Shuttleworth 2008).

Scintillometer – A device that uses a theoretical relationship between sensible and latent heat fluxes and atmospheric scintillation introduced into a beam of electromagnetic radiation between source and detector by temperature and humidity fluctuations (Shuttleworth 2008).

Soil water balance – *Soil Moisture Content*; The ratio of the volume of contained water in a soil compared with the entire soil volume. When a soil is fully saturated, water will drain easily into the underlying unsaturated rock. When such drainage stops, the soil still retains capillary moisture and is said to contain its field-capacity moisture content. Further drying of the soil (e.g. by evapotranspiration) creates a soil-moisture deficit, which is the amount of water which must be added to the soil to restore it to field capacity measured as a depth of precipitation (Allaby and Allaby 1991).

Stoma – A small pore in a plant leaf or stem that allows the transfer of water vapor and gas.

Succession – Seral stages – successive plant communities that follow one another in time on a given site (Peale 1996).

Transpiration – The removal of moisture from the soil by plant roots, its translocation up the stem to the leaves, and its evaporation through the stomata (Allaby and Allaby 1991).

Upper Colorado River Basin – The Colorado River Watershed beginning at its headwaters in Colorado's Rocky Mountains and extending downstream to Lee's Ferry just below Glen Canyon Dam. The Upper Basin covers portions of Arizona, Colorado, New Mexico, Utah, and Wyoming.

Upper floodplain terraces – Lands within the floodplain but with a deeper water table that would normally be occupied by more xeric native vegetation.

Xeric – Having very little moisture; tolerating or adapted to dry conditions (Lincoln et al. 1998).

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