Converting Riparian Restoration Waste to Energy: Testing Tamarisk (*Tamarix* spp.) Woody Biomass as Fuel for Downdraft Gasification

Jamie Nielsen, James Diebold, Tillie Walton, Michael Boyle and Robb Walt

ABSTRACT

In the course of riparian ecological restoration work, tamarisk biomass is often piled and burned, generating air pollution, or shipped to landfills—a costly alternative. Information on processing and utilizing tamarisk biomass is becoming increasingly valuable in light of the spread of the tamarisk leaf beetle (*Diorhabda* spp.) as a biological control agent. As beetle populations expand, information on the properties of both green and beetle-killed tamarisk biomass and their suitability as feedstocks for conversion to energy will be useful for land managers seeking to offset the costs of tamarisk removal, restore wildlife habitat and ecosystem function, and reduce wildfire threat posed by standing dead tamarisk. Field trials, feasibility studies, and economic analyses are needed to enable pioneering restorationists and land managers to incorporate tamarisk biomass utilization into their project plans. We collected both green (live) and dead tamarisk impacted by the tamarisk leaf beetle and tested both as fuels for conversion to a clean producer gas via downdraft gasification and then to electricity in a spark-ignited engine/genset at Community Power Corporation in Littleton, Colorado. Both green and dead tamarisk chips were good fuels for gasification, performing more efficiently than a sample of mixed softwood. Further, the data suggest that significantly more energy can be recovered from tamarisk when harvested green, compared to waiting for the tamarisk to die and age. When incorporated into a comprehensive restoration plan, tamarisk appears to have potential to be used as a valuable energy source rather than viewed as unwanted waste.

Keywords: biomass utilization, gasification, invasive species, riparian restoration, tamarisk (*Tamarix* spp.), tamarisk leaf beetle (*Diorhabda* spp.)

Riparian ecosystems constitute a very small percentage of the total land area in the southwestern United States but support a high diversity of plant and animal species and provide critically important ecosystem services. Altered flow regimes on rivers, agriculture, livestock grazing, and introduced exotic species, among other human-related activities, have contributed to the rapid decline of these valuable ecosystems (Briggs 1996). Tamarisk, or saltcedar, (*Tamarix* spp.), an invasive woody shrub introduced to North America in the mid 19th century, is now widely distributed on river systems, reservoirs, and perennial drainages throughout the southwestern United States. Highly tolerant of drought and saline soils, tamarisk is well adapted to growing conditions in riparian areas impacted by altered hydrologic cycles on dammed rivers (Glenn and Nagler 2005). Dense stands of tamarisk increase sedimentation in river channels (Zavaleta 2000, Birken and Cooper 2006) and contribute to increased salinity of surface soils (DiTomaso 1998, Tamarisk Coalition 2009). Tamarisk is a fire-adapted species, believed to play a role in increased wildfire frequency and intensity in riparian corridors (Ellis 2001, Zouhar 2003, Glenn and Nagler 2005). Dense, monospecific tamarisk stands support a lower diversity of arthropods and bird species with specific habitat requirements than mixed stands of native vegetation and tamarisk (Bateman and Paxton 2010).

While many researchers and practitioners maintain that native riparian vegetation cannot become sustainably reestablished on altered river systems until natural (historic) river flow regimes are restored, government and private land managers continue to allocate millions of dollars to tamarisk removal and restoration of native vegetation (Zavaleta 2000, Shafroth et al. 2008). Following tamarisk removal, tamarisk biomass reduction is often an important step in preparing a site for planned revegetation efforts (Tamarisk

Ecological Restoration Vol. 29, No. 3, 2011
ISSN 1522-4740 E-ISSN 1543-4079

Coalition 2009, Dykstra 2010). In the course of riparian restoration work, tamarisk biomass is often piled and burned, increasing soil salinity and generating smoke, particulates, and greenhouse gases, or shipped to landfills where it reduces landfill capacity and generates carbon dioxide (CO_2) and methane (CH_4) emissions as it degrades over time (Morris 1999). Mulching is another option for biomass reduction, but a thick layer of mulch can actually impede or prevent establishment and growth of desired vegetation (Tamarisk Coalition 2009), and mulching can compromise access to the soil surface for seeding or soil amendments (Sher et al. 2010). An alternative option for tamarisk biomass reduction—utilizing tamarisk as a feedstock for conversion to energy—has the potential to be more economical and environmentally sound than open burning, landfilling, or heavy mulching. Ideally, demand for tamarisk biomass could help reduce the cost per hectare of riparian restoration, releasing funds for allocation to those project components that are most often underfunded—revegetation, long-term monitoring, and maintenance.

Information on the processing and utilization of tamarisk biomass is becoming increasingly valuable in light of the spread of a tamarisk biological control agent. Species of tamarisk leaf beetle (*Diorhabda* spp.) were approved by the U.S. Department of Agriculture (USDA) for release in 2001 and are generating tens of thousands of hectares of weakened and dead tamarisk. Tamarisk leaf beetles are now widely dispersed in the western U.S., defoliating tamarisk in Arizona, California, Colorado, Nevada, Texas, and Utah (Tamarisk Coalition 2009, O'Meara et al. 2010). In June 2010, in response to concerns that the biological control of tamarisk could negatively impact the endangered southwestern willow flycatcher (*Empidonax traillii extimus*), which has been observed nesting in tamarisk where preferred native vegetation is not present, the USDA issued a moratorium discontinuing permits for interstate movement and release of tamarisk leaf beetles and terminated the federal tamarisk biological control program (USDA APHIS 2010). Nonetheless, tamarisk leaf beetles are widely distributed in many western states, and state-level tamarisk biological control programs will continue their research and monitoring in most cases (Bean 2010). Predictive models based on the beetles' native habitat and range indicate that some species could potentially expand as far north as Wyoming and others as far south as the deserts of Arizona and southern California (Tracy et al. 2009).

While little is known about long-term ecological impacts of the tamarisk leaf beetle, large areas of tamarisk, weakened or killed by repeated defoliation, are creating new conservation challenges. As beetle populations expand, information on the properties of both green and beetle-killed tamarisk biomass and their suitability as feedstocks for conversion to energy will be useful for land managers seeking to offset the costs of tamarisk removal, restore wildlife habitat and ecosystem function, reduce hazardous fuels, and improve fire prevention and suppression in riparian and other sensitive areas.

Restorationists with an abundance of live or beetle-impacted tamarisk on their project sites face several barriers to incorporating biomass utilization into their management plans. Among these obstacles is difficulty accessing project sites in remote areas with heavy equipment and vehicles and difficulty operating chippers and other harvesting equipment on uneven terrain and soft soils. Steep canyon walls and deep sand or mud can be physical barriers to harvesting biomass at project sites in wetlands and riparian areas. The costs of transporting woody biomass from collection site to processing facility (combustion site) can also be prohibitive. The economically viable distance for transportation of wood chips has been estimated at between 54 and 161 km (Bilek et al. 2005), with an average viable transportation radius of up to 80 km from collection to combustion sites used as a general rule of thumb (EIA 1998). Operators of biomass-to-energy facilities have expressed concerns over the corrosiveness of tamarisk to their machinery, due to high salt content and the potential for elevated levels of "trash" (dirt and dust) in tamarisk chips, both of which may lead to increased maintenance costs for wood boiler, gasifier, and other wood-to-energy systems. Finally, in light of bark beetle outbreaks and wildfire reduction forest thinning operations, some regions of the western U.S. enjoy a ready supply of softwood biomass that is easier and more cost-effective to utilize than tamarisk.

Despite these barriers, tamarisk biomass utilization has the potential to become an important component of riparian restoration projects, reducing or eliminating the costs and the negative environmental impacts currently associated with biomass reduction. The major limiting factors to tamarisk biomass utilization will be site and project specific, and must be analyzed on a case-by-case basis. Field trials, feasibility studies, and economic analyses are needed to enable pioneering restorationists and land managers to incorporate tamarisk biomass utilization into their project plans.

Analyses of tamarisk wood properties and wood chemistry have been conducted over time, but methodology, quality, and availability of results are extremely varied. Baseline information was generated by the U.S. Forest Service Forest Products Laboratory (FPL) in 1939 and 1940, in a study of basic wood properties of Athel tamarisk (*Tamarix aphylla*), including moisture content and bending and compression properties (Gerry 1954). More recently, the U.S. FPL has conducted research on the mechanical properties of tamarisk wood-plastic composites, which included testing tamarisk wood flour for mineral content and water-soluble

Figure 1. Tamarisk being chipped on-site. A gentle crosswind separates dirt and dust from tamarisk chips that the collection site. Photos by M. Boyle.

extractive content (Clemons and Stark 2009). A broad range of technologies for converting woody biomass to heat and energy have been developed, but information is needed on how green and beetle-killed tamarisk, in particular, will perform as feedstocks for these technologies. The general consensus is that tamarisk could be utilized in the same manner as other woody biomass in gasifiers, combined heat/power systems, or other "burn" systems, such as pellet stoves (Next Earth 2007). Sustainable Communities (2006) conducted a study on the conversion of tamarisk wood to charcoal, but to the best of our knowledge no information on beetle-killed tamarisk—as compared to green (live) tamarisk—conversion to energy is currently available in the literature.

Gasification is the conversion of a carbon-rich material, or feedstock, to a combustible synthesis gas, which can be used in place of fossil fuels. Today's gasifier systems can produce electricity and thermal energy from a range of feedstocks, including hard and soft wood chips; biomass residues such as sawdust, corn stover, hay, grape skin, and nut shells; and waste paper and cardboard. The family of BioMax® downdraft gasifiers was developed by Community Power Corporation (CPC) in Littleton, Colorado, with funding from the U.S. Departments of Energy, Agriculture, and Defense. The BioMax® 25 is a renewable energy system that converts biomass to a renewable fuel gas that can then be converted into other forms of energy including mechanical, electrical, thermal, chemical, or liquid fuels (CPC 2010). The photosynthetic energy stored in the feedstock is converted to producer gas, which is cleaned and used to fuel an internal combustion engine, which in turn spins a generator producing electrical power. The fuel gas generated by woody feedstocks is typically composed of about 20% carbon monoxide (CO), 20% hydrogen (H_2) and 2% CH_4 (CPC 2010).

The byproduct of biomass gasification is a black ash, or residual char, which contains the original mineral matter of the biomass feedstock and some residual carbonaceous material. The gasification unit used in this study produces no smoke, and meets the California Air Resources Board emissions standards—the most stringent in the United States. The byproducts and emissions generated by the gasification process may be relevant for restorationists and practitioners not only on the basis of environmental stewardship, but also in terms of the economic and regulatory feasibility of building a woody biomass utilization component into a restoration project plan.

Sample Collection: Lessons Learned in the Field

We collected tamarisk biomass samples at 2 sites adjacent to the Colorado River near Moab, Utah. The taxa that comprise the majority of invasive tamarisk in this region and across western North America are saltcedar (*Tamarix ramosissima*), five-stamen tamarisk (*T. chinensis*), and *T. ramosissima* × *T. chinensis* hybrids (Shafroth et al. 2008). Although genetically distinct, the 2 species are difficult to distinguish morphologically. Genetic analysis confirms a high rate of hybridization and indicates that a large percentage of invasive tamarisk in the U.S. is a part of one continuum between the 2 parental types (Gaskin and Kazmer 2009).

We chose collection sites based on availability of green (live) tamarisk, as well as standing dead tamarisk that has been impacted by the tamarisk leaf beetle. Both sites had the advantage of easy road access for crews and equipment. Site 1 was a dense monoculture of green tamarisk on private property, roughly 1.62 ha in size, on a floodplain adjacent to the Colorado River, north of Moab, Utah. Site 2, a potash mine adjacent to the Colorado River, was one of the first tamarisk leaf beetle release sites in the vicinity of Moab, Utah.

Green, stressed, and dead tamarisk were present at Site 2, with large quantities of beetle-killed tamarisk available for collection. Although it is difficult to pinpoint the exact point of biocontrol-impacted tamarisk mortality, a rough estimate can be formed in this case, based on the dates of the original beetle release here and the first observations of tamarisk mortality at the site. The tamarisk leaf beetle was first released at the Potash Mine site in August of 2004, initiating repeated defoliations followed by tamarisk refoliation over multiple seasons. Grand County Weed Managers report the first observed tamarisk mortality (absence of refoliation) in 2008 (Higgs 2011), so the stems felled and chipped for our sample had most likely been dead and drying for 1 to 2 years.

We chose to employ hand clearing at Sites 1 and 2, as opposed to mechanized removal with heavy machinery. Hand clearing results in less soil disturbance than mechanized removal and is useful where existing native vegetation is established because workers can discriminate between native and non-native vegetation, leaving native plants intact. A professional, 3-person clearing crew used chainsaws to fell and buck the trees and a chipper to convert the material to chips of 3.8 to 6.4 cm in size. Initially, we used a 15.2-cm diameter, gasoline-powered Vermeer chipper at Site 1, but this chipper generated a shredded mulch that can cause jams as it is fed into a downdraft gasifier. A larger-diameter, 30.5 cm diesel-powered, Vermeer chipper generated the correct chip size, and it processed the tamarisk significantly faster, allowing the crew to work more efficiently overall. The larger-diameter chipper was also more economical, using 3.8 L of diesel fuel per hour, as opposed to the smaller-diameter chipper, which used roughly 6.4 L of gasoline per hour. With the chipper running approximately 1 hr at each site, the crew generated 274.9 kg of green tamarisk chips and 225 kg of beetle-killed tamarisk chips at Sites 1 and 2, respectively. The dry weight of the 2 samples was almost identical.

One of the major barriers to tamarisk biomass utilization identified by land managers who have piloted biomass-to-energy projects is difficulty producing "clean" (free of dust or soil) chipped or shredded woody material (Next Earth 2007). Dust, dirt, and other trash can cause ash fusion when combusted in wood boilers or gasified. At both sites, we found that a light crosswind effectively separated dust from the chips as they were blown out of the chipper into piles (Figure 1). More particulate matter was removed from the samples during screening at CPC, prior to gasification. Chips were collected in heavy-duty, clear plastic bags, sealed with duct tape, and separately labeled. Each bag contained approximately 27–32 kg of chipped material. The bags were secured to pallets and shipped to CPC in Littleton, Colorado, for drying, screening, and gasification.

Sample Preparation and Preliminary Analysis

At CPC, initial moisture content was measured for both samples, and a vibrating screener was used to separate samples into size categories. The sample of beetle-killed tamarisk had an initial moisture content of 16%, which was sufficiently low for gasification without further drying. However, the screening process resulted in additional moisture loss, bringing the moisture content to measured values of 9.4% and 11.4% before gasification. The initial moisture content of the green sample was more variable, with 3 measured values of 24.7%, 29.7%, and 32%. The green chips were air dried at the testing facility for 3 days, reducing the moisture content to 9% before gasification.

Beetle-killed and green samples contained nearly identical percentages by weight of "overs" (chips that were too large to be used in the BioMax), but the beetle-killed sample contained a larger percentage of "unders" (chips that were too small to be used in the BioMax). Consequently, the green sample contained nearly 10% more usable chips than the beetle-killed sample. The percentage of usable fractions by weight can be influenced by the condition of the biomass when harvested, chipper make and model, and the condition and positioning of chipper blades.

Before being tested in the gasifier, we sent representative samples of both beetle-killed and green tamarisk to Hazen Research, Inc. for elemental and constituent analyses, and to measure heating values and ash fusion temperatures. Ash fusion at high temperatures is desirable in a biomass feedstock, as ash fusion at lower temperatures, referred to as "clinkering," causes gas-flow problems through the gasifier grate and requires regular maintenance.

Table 1 lists results of the preliminary analysis of both samples. Results from analysis of a third sample, composed of mixed softwood chips, are

Table 1. Results of preliminary analysis of dead tamarisk, green tamarisk, and mixed softwood samples: ultimate and proximate analyses, higher heating value (HHV) and lower heating value (LHV) in MJ/kg and Btu/lb, sodium and potassium content, ratio of sodium to potassium, and ash fusion temperatures.

Test Parameter	Dead Tamarisk	Green Tamarisk	Mixed Softwood Chips 5/18/10
Feedstock Proximate Analysis			
Ash, %	3.55	2.99	0.86
Volatile, %	85.44	85.99	86.83
Fixed C, %	11.01	11.02	12.31
Total, %	100.00	100.00	100.00
Sulfur, %	0.716	0.608	0.006
Feedstock Ultimate Analysis			
Carbon, %	49.46	49.69	52.32
Hydrogen, %	5.39	5.50	6.35
Nitrogen, %	0.23	0.19	0.32
Sulfur, %	0.72	0.61	<0.01
Ash, %	3.55	2.99	0.86
Oxygen, % (by difference)	40.65	41.02	40.15
Feedstock Heating Value			
HHV, MJ/kg (Btu/lb)	18.28 (7861)	19.07 (8200)	19.6 (8400)
LHV, MJ/kg (Btu/lb)	17.11 (7355)	17.87 (7684)	18.1 (7804)
Water-Soluble Alkalies			
Sodium as Na_2O, %	0.331	0.243	0.0076
Potassium as K_2O, %	0.279	0.205	0.068
Na_2O / K_2O w/w	1.186	1.185	0.112
Ash Fusion Temperature			**Softwood Pellets 2/20/06**
Reducing Atmosphere			
Initial, °C (°F)	1396 (2544)	1427 (2601)	1207 (2204)
Softening, °C (°F)	1404 (2560)	1435 (2615)	1215 (2219)
Hemispherical, °C (°F)	1413 (2575)	1439 (2623)	1221 (2229)
Fluid, °C (°F)	1417 (2583)	1444 (2631)	1231 (2247)
Oxidizing Atmosphere			
Initial, °C (°F)	1327 (2420)	1389 (2532)	1232 (2249)
Softening, °C (°F)	1331 (2428)	1400 (2552)	1235 (2255)
Hemispherical, °C (°F)	1343 (2450)	1404 (2560)	1244 (2271)
Fluid, °C (°F)	1349 (2460)	1410 (2570)	1247 (2277)

included to provide a basis for comparison. The mixed softwood chip sample was harvested in the Rocky Mountain region, but information on species composition and condition when harvested (dead or green) was unavailable for this sample. For comparative purposes, Table 2 provides ultimate and proximate analyses of pure samples of ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), and white fir (*Abies concolor*) (ECN 2011), alongside the CPC mixed softwood sample. Values for these 3 species are fairly consistent with the CPC mixed softwood sample of unknown species.

The net heat of combustion, or lower heating value (LHV), is the quantity of heat liberated by the complete combustion of one unit of a substance, under conditions such that all water in the products remains in the form of vapor and the latent heat of vaporization is not recovered. In our study, the LHV indicates the amount of heat produced by gasification of tamarisk, when the moisture in the flue gasses produced remains as a vapor. In contrast to LHV, the gross heat of combustion, or higher heating value (HHV), is obtained by complete combustion of one unit of a substance, where all products are cooled to their pre-combustion temperature, water vapor is condensed, and the latent heat of vaporization is recovered. The beetle-killed tamarisk sample had an LHV of 7,355 Btu/lb, and the green tamarisk had an LHV of 7,684 Btu/lb, both of which are comparable with the 7,804 Btu/lb of the softwood sample, but reflect a higher ash content.

Ash contents for beetle-killed and green samples were 3.55% and 2.99%, respectively, while the ash content of the softwood sample was only 0.86% (Table 1). Ash content of tamarisk was 3–4 times higher than that of the softwood sample. Much of this increase in ash content is likely due to the elevated sodium and potassium content in the tamarisk samples, 0.331% and 0.297%, respectively. The ratio of sodium to potassium for the tamarisk samples was unusually high and remarkably consistent at 1.185 and 1.186, compared to the sample of softwood chips at 0.112. Ash fusion temperatures for the tamarisk samples were 95°C–220°C higher than the softwood sample, so formation of clinkers during gasification at lower temperatures is not expected. However, the higher ash content in the tamarisk samples has the potential to form more undesirable clinkers if localized hot spots are present in the gasifier. Ash content and HHV from our preliminary analysis are consistent with analyses of charcoals produced from tamarisk and 5 other woody species, where the tamarisk charcoal was reported to have a higher ash content and a lower HHV than the charcoal produced from ponderosa pine (Sustainable Communities 2006).

Green tamarisk had higher heating values and lower ash content than the beetle-killed tamarisk on a dry wood basis. This suggests that the wood of the tamarisk killed by repeated defoliation lost significant mass and heating value. If the ash content is assumed to have been the same in the 2 tamarisk samples while alive, then the trees lost 15.8% of their mass during dying and in the years after their death. If we further assume that the energy content in the wood from the trees at Sites 1 and 2 was initially identical, then an energy balance suggests that the LHV of this missing mass is 9,437 Btu/lb. The beetle-killed tamarisk apparently lost 19.4% of its energy while dying and aging.

Table 2. Comparative ultimate and proximate analyses of pure (not mixed) softwood species and the CPC mixed softwood chip values from Table 1: higher heating value (HHV) and lower heating value (LHV) in MJ/kg and Btu/lb. Values for single-species softwood samples are consistent with values for the mixed softwood sample. Pure species data courtesy of ECN (2011).

Feedstock Test Parameter	Dry Ponderosa Pine*	Dry Lodgepole Pine*	Dry White Fir*	Mixed Softwood Chips 5/18/10
Proximate Analysis				
Ash, %	0.3	4.7	0.3	0.86
Volatiles, %	82.5	60.6	83.2	86.83
Fixed Carbon, %	17.2	34.7	16.5	12.31
Total, %	100.0	100.0	100.0	100.00
Sulfur, %	0.03	Not detected	0.01	0.006
Ultimate Analysis				
Carbon, %	49.3	51.1	49	52.32
Hydrogen, %	5.99	5.91	5.98	6.35
Nitrogen, %	0.06	0.1	0.05	0.32
Sulfur, %	0.03	Not Detected	0.01	<0.01
Ash, %	0.3	4.7	0.3	0.86
Oxygen, % (by difference)	44.4	38.2	45.0	40.15
Heating Value				
HHV, MJ/kg (Btu/lb)	20.0	18.9	19.9	19.6 (8400)
LHV, MJ/kg (Btu/lb)	18.7	17.5	18.6	18.1 (7804)

Gasification

The 2 tamarisk samples were gasified separately at CPC, using the open-top research BioMax® 25 gasifier. The producer gas made from our tamarisk samples was used to fuel a research-configured, 4.3L, 4-cylinder, GM Vortec–powered engine/genset. Producer gas composition was monitored with a NOVA Model 7900P5, which analyzed the gas for O_2, CO, CO_2, CH_4, and H_2.

A total of 152.36 kg of beetle-killed tamarisk chips were fed into the feed hopper over a period of 5 hr and 42 min. The quality of the producer gas from this sample was good, having a thermal energy content of 95.7 kW (Table 3). The average electrical power generated by the engine/genset fueled by the gas was 24.2 kWe.

Based on the LHV from preliminary testing (Table 1) and an average feeding rate of 22.3 kg of chips per hour into the gasifier, the average thermal energy input into the gasifier was 106 kW. This results in an apparent conversion of 90% of the wood energy into producer gas—about 10 percentage points higher than expected, based on results from gasification of other woody feedstocks tested at CPC. The efficiency of conversion of the thermal energy in the beetle-killed wood to electricity was equal to or greater than 22.9%.

A total of 151 kg of green tamarisk chips were fed into the feed hopper over a period of 6 hr and 41 min. The quality of the producer gas from the green sample was also good, with a thermal energy content of 90.1 kW. The average electrical power generated by the engine/genset fueled by the gas was 24.6 kWe.

Based on the LHV from preliminary testing (Table 1), and an average feeding rate of 19.6 kg (43.2 lbs) per hour, the average thermal energy input into the gasifier was 97.3 kW. This results in an apparent conversion of 92.6% of the wood energy into producer gas—about 13 percentage points higher than expected. The efficiency of conversion of the thermal energy in the green tamarisk wood to electricity was 25.3%. By comparison, the efficiency of conversion of the thermal energy in the softwood sample was only 23%.

Both green and dead tamarisk chips were excellent fuels for gasification in the BioMax® 25 gasifier. In these tests, the energy efficiency of the conversion of wood to producer gas was extremely efficient for tamarisk, compared to the softwood data. Part of this increase in efficiency can be explained by the apparently more complete gasification of the char. The yield of char from the tamarisk samples was almost the same as the ash content, while analysis of the char from the softwood sample found that it still contained about 50% combustible material.

The yield of producer gas from the tamarisk samples was slightly lower

Table 3. Comparative performance data for gasification of beetle-killed tamarisk chips, green tamarisk chips, and mixed softwood chips: conversion efficiencies; yield of producer gas in normal cubic meters per kilogram (Nm^3/kg) (a metric expression of gas volume); producer gas composition; LHV in MJ/Nm^3; producer gas thermal energy content; electrical power generated by each producer gas when powering the engine/genset; and char yield as a percentage by weight. Note: Conversion efficiency calculations were based on net feed (the amount of wood actually fed into the gasifier), not on gross amount of material received from the field, which included "unders" and "overs."

Performance Parameter	**Beetle-Killed Tamarisk** 152.36 kg (335.9 lbs)	**Green Tamarisk** 151 kg (333 lbs)	**Mixed Softwood**
Conversion Efficiencies			
Dry wood to producer gas, % energy efficiency	90.4	92.4	82.9
Dry wood to electricity, % energy efficiency	≥ 22.9	25.3	23.0
Yield			
Amount of producer gas generated per kg of wood chips, Nm^3/kg	3.00	3.03	3.22
Producer Gas Composition (dry basis)			
O_2, vol %	0.2	0.4	0.6
CO, %	24.1	24.0	19.5
CO_2, %	12.1	9.6	10.6
CH_4, %	3.8	3.3	2.4
H_2, %	16.5	16.5	16.3
N_2, %	42.3	46.2	50.6
Net Heat of Combustion (LHV) of Producer Gas			
Dry basis, MJ/Nm^3	6.20	5.98	5.06
Wet basis, MJ/Nm^3	5.64	5.43	4.65
Producer gas thermal energy content, kW	95.7	90.1	82.6
Avg. electrical power generated, kW_e	24.2	24.6	23.2
Ash, wt% (from Table 1)	3.55	2.90	0.86
Char yield, wt%	2.66	3.10	3.44

than from the softwood sample, but its composition was much richer in CO and CH_4 (Table 2), resulting in higher heating values and overall energy conversion (higher efficiency of conversion). The lower moisture content of the tamarisk samples when gasified, compared to the softwood sample, resulted in lower system energy losses required to evaporate it, which resulted in a producer gas with higher energy content. The higher moisture content of the softwood is thought to have contributed to its lower efficiency of conversion to energy in the producer gas, as the heat required to vaporize moisture was not recovered.

Testing the Byproducts of Gasification

The byproducts of gasification of green tamarisk—coarse and fine residual char/ash—were sent to Accutest Laboratory for pH testing, as well as the Environmental Protection Agency's (EPA) Toxic Characteristic Leachate Procedure (TCLP) SW-846 1311. The TCLP helps identify wastes likely to leach concentrations of contaminants that may be harmful to human health or the environment (USEPA 2009). TCLP analysis was used to test our residual material for traces of 8 heavy metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. This analysis revealed trace levels of barium (2.2 mg/L) and selenium (0.029 mg/L), but neither sample contained heavy metals in concentrations that approached the EPA's regulatory limits of 100 mg/L and 1.0 mg/L, respectively (EPA 2010). The pH values were high, as is normal for wood ash, with the coarse char having a pH value of 11.91 and the fine char a pH value of 12.35. These high pH values indicate the value of this residual material as a liming fertilizer to amend acidic soils and are probably due to sodium, potassium, and calcium carbonates present in the chars.

Summary and Discussion

Both green and dead tamarisk chips performed well as fuels for gasification in the BioMax® 25 gasifier. In these tests, tamarisk appeared to perform more efficiently than softwood as a fuel for gasification, due to more thorough gasification of the tamarisk char. This difference in gasification efficiency was also due to higher moisture content in the softwood tested. The engine/genset was equally efficient with producer gas from tamarisk or softwood samples.

A downdraft gasification system installed at a municipal building, school, or other such facility, in close proximity to an ongoing riparian restoration project site, could provide both power and heat to the host facility. In addition, the significant costs of landfilling or fire mitigation planning could be eliminated, and that portion of the project budget allocated to other components of the restoration plan.

The host facility would benefit from energy savings, and rebate incentives at the federal and state levels, where available, could help to offset the cost of system purchase and installation. When the local supply of tamarisk is exhausted, a wide range of alternative feedstocks can serve as fuel for the gasification unit, including nonrecyclable office or cafeteria waste generated by the host facility. Additional factors conducive to a successful tamarisk gasification project might include a large quantity of tamarisk being removed over time, high regional energy costs, and utility company participation. As an alternative, a public land management agency involved in tamarisk removal in multiple areas might consider a portable gasification unit. In response to costs associated with biomass transportation, manufacturers have begun making smaller, modular, portable gasification units.

When viewed in the context of power generation, the data strongly suggest that significantly more energy can be recovered from green tamarisk than dead tamarisk. Based on the higher ash content of the dead tamarisk, it appears that 15.8% of the dry weight containing 19.4% of the energy of the wood was lost. In addition, the chipping of dead tamarisk wood produced 10% less usable woodchips, compared to the higher usable yield from green tamarisk. In combination, these data suggest that harvesting the tamarisk while green will result in 37% more energy recovery, compared to harvesting the same tamarisk after it has succumbed to repeated defoliation and the standing dead biomass has aged and dried. We recommend that additional testing be conducted with green and dead samples from a range of sites in multiple geographic regions to verify this conclusion.

On the other hand, when these findings are viewed in the context of ecological restoration, this information has implications for a broad range of planning and management decisions based on short- and long-term management objectives and would need to be evaluated on a site by site basis. Implications of higher energy recovery from green (live) tamarisk woody biomass vs. dead can vary as widely as project objectives and land management mandates, which range from wildlife habitat improvement, to wildfire prevention, to enhancement of ecosystem functions.

Conclusion

While tamarisk removal efforts in the southwestern U.S. continue and the tamarisk leaf beetle increases its range, finding alternative uses for tamarisk becomes an increasingly important factor in riparian restoration efforts. Finding productive uses for the unwanted tamarisk can help to offset costs of hauling biomass to landfills and eliminates the need to burn tamarisk on site, which can result in costly fire-mitigation planning, unintended spread of wildfire, and the release of smoke, ash, and carbon into the atmosphere.

As new information on utilizing non-native, invasive species for conversion to energy becomes available, it is imperative that restorationists continue to emphasize the importance of placing biomass reduction (harvesting) within the context of a larger, comprehensive ecological restoration plan. Removing large quantities of biomass without site assessment, a comprehensive project plan, regulatory compliance measures, sufficient funding, and community and stakeholder involvement, where possible, could result in serious negative environmental impacts. Site conditions and project objectives vary widely, but a restoration plan that includes revegetation with native species and ongoing monitoring and maintenance has a higher likelihood of successfully re-establishing diverse riparian plant communities.

Although the results presented here comprise only a small piece in a larger puzzle of logistical and economic challenges, we hope to provide some useful information on the process of tamarisk biomass collection and the value of tamarisk as a fuel for downdraft gasification. In a broader sense, before beetle-impacted tamarisk removed from restoration sites can be viewed as a resource rather than waste, its value as a fuel for energy production must be clearly demonstrated by a substantial body of field trials, research, and economic analysis. Our findings indicate that there is potential for converting this negative value waste material into an energy-generating resource. Financial analyses specific to the utilization of tamarisk removed from riparian areas and research detailing the overall energy balance of tamarisk-to-energy projects would make valuable contributions to this field and to the limited body of information that is currently available.

Acknowledgements

The Working for Rivers Foundation would like to thank the following organizations for their support and contributions to this project: CPC, for being willing to test a new type of woody biomass and for their thorough analysis and detailed reporting; Davida and Ron Herzl, for laying the ground work for this project, arranging the site visits, and researching possible alternative uses of tamarisk; and the folks at Wildland Scapes in Moab who made the field collection efficient and effective.

References

Bateman, H.L. and E.H. Paxton. 2010. Saltcedar and Russian olive interactions with wildlife. Pages 49–63 *in* P.B. Shafroth, C.A. Brown and D.M. Merritt (eds), Saltcedar and Russian Olive Control Demonstration Act science assessment. U.S. Geological Survey Scientific Investigations Report 2009–5247.

Bean, D. 2010. Personal communication on August 23. Colorado Department of Agriculture, Biological Pest Control Program, Program Administrator and Insectary Manager.

Bilek, E.M., K.E. Skog, J. Fried and G. Christensen. 2005. Fuel to burn: economics of converting forest thinnings to energy using BioMax in southern Oregon. Gen. Tech. Rep.

FPL-GTR-157. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Birken, A.S. and D.J. Cooper. 2006. Processes of *Tamarix* invasion and floodplain development along the lower Green River, Utah. *Ecological Applications* 16:1103–1120.

Briggs, M.K. 1996. *Riparian Ecosystem Recovery in Arid Lands, Strategies and References*. Tucson: The University of Arizona Press.

Clemons, C.M and N.M. Stark. 2009. Feasibility of using saltcedar as a filler in injection-molded polyethylene composites. *Wood and Fiber Science* 41:2–12.

Community Power Corporation. 2009. FAQs: What is a BioMax®? www.gocpc.com/faq.html.

Di Tomaso, J.M. 1998. Impact, biology, and ecology of saltcedar (*Tamarix* spp.) in the southwestern United States. *Weed Technology* 12:326–336.

Dykstra, D.P. 2010. Extraction and utilization of saltcedar and Russian olive biomass. Pages 105–116 in P.B. Shafroth, C.A. Brown and D.M. Merritt (eds), Saltcedar and Russian Olive Control Demonstration Act science assessment. U.S. Geological Survey Scientific Investigations Report 2009–5247.

ECN, 2011. Energy Research Center of the Netherlands. www.ecn.nl/phyllis.

Energy Information Administration. 1998. Challenges of electric power industry restructuring for fuel suppliers. Department of Energy Report DOE/EIA-0623. www.eia.doe.gov/pub/electricity/chg_str_fuel.pdf.

Ellis, L.M. 2001. Short-term response of woody plants to fire in a Rio Grande riparian forest, central New Mexico, USA. *Biological Conservation* 97:159–170.

Gaskin, J.F. and D.J. Kazmer. 2009. Introgression between invasive saltcedars (*Tamarix chinensis* and *T. ramosissima*) in the USA. *Biological Invasions* 11:1121–1130.

Gerry, E. 1954. Athel Tamarisk *Tamarix aphylla* (L.) Karst. (= *T. articulata* Vahl.) Family: Tamaricaceae. U.S. Forest Service, Forest Products Laboratory, information leaflet, Foreign Woods Series Report 1986. Madison, WI.

Glenn, E.P. and P.L. Nagler. 2005. Comparative ecophysiology of *Tamarix ramosissima* and native trees in western U.S. riparian zones. *Journal of Arid Environments* 61:419–446.

Higgs, T. 2011. Personal communication on April 28. Grand County Utah Weed Department, County Weed Control Supervisor.

Morris, G. 1999. The value of the benefits of U.S. biomass power. NREL/SR57027541. Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy00osti/27541.pdf.

Next Earth Foundation. 2007. A pilot project for incorporating economic-benefit models into riparian restoration: creating jobs via alternative uses for tamarisk in the Lower Colorado River Region. A preliminary report prepared for Working for Rivers Foundation, Flagstaff AZ.

O'Meara, S., D. Larsen and C. Owens. 2010. Methods to control saltcedar and Russian olive. Pages 65–102 in P.B. Shafroth, C.A. Brown and D.M. Merritt (eds), Saltcedar and Russian Olive Control Demonstration Act science assessment. U.S. Geological Survey Scientific Investigations Report 2009–5247.

Shafroth, P., V. Beauchamp, M. Briggs, K. Lair, M. Scott and A. Sher. 2008. Planning riparian restoration in the context of *tamarix* control in western North America. *Restoration Ecology* 16:97–112.

Sher, A., K. Lair, M. DePrenger-Levin and K. Dohrenwend. 2010. Best management practices for revegetation after tamarisk removal in the upper Colorado River basin. Colorado: Denver Botanic Gardens.

Sustainable Communities. 2006. Chart of charcoal test results, May 2006 update. Zero Emissions Research & Initiatives, New Mexico. www.scizeri-nm.org/ZERI/_PDF/chartfinalmad.pdf.

Tamarisk Coalition. 2009. Colorado River Basin tamarisk and Russian olive assessment. Prepared for 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. http://tamariskcoalition.org/ColoradoRiver.html.

Tracy, J.L., M. Di Luzio and C.J. DeLoach. 2009. Ecoclimatic species distribution models of tamarisk beetles (*Diorhabda elongata* species group) and invasive tamarisks (*Tamarix* spp.) with a novel stacked environmental envelope model (SEEM). Abstract in 2009 Tamarisk and Russian Olive Research Conference. Reno, NV: Tamarisk Coalition and Colorado State University. www.coopext.colostate.edu/TRA/PLANTS/weeds/Tamarisk_2009.shtml

U.S. Environmental Protection Agency. 2009. Hazardous waste characteristics: a user-friendly reference document. www.epa.gov/osw/hazard/wastetypes/wasteid/char/hw-char.pdf.

Electronic Code of Federal Regulations. 2010. 40 CFR, part 261.24 (b), Table 1, Maximum Concentration of Contaminants for the Toxicity Characteristic. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&rgn=div8&view=text&node=40:25.0.1.1.2.3.1.5&idno=40.

U.S. Department of Agriculture. 2010. Plant Protection and Quarantine. USDA APHIS PPQ Moratorium for Biological Control of Saltcedar (*Tamarix* species) using the Biological Control Agent *Diorhabda* Species (Coleoptera: Chrysomelidae). Issued June 15. Print.

Zavaleta, E. 2000. The Economic Value of Controlling an Invasive Shrub. *Ambio* 29:462–467.

Zouhar, K. 2003. *Tamarix* spp. In Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. www.fs.fed.us/database/feis.

Jamie Nielsen (info@workingforrivers.org), Tillie Walton, and Michael Boyle: The Working for Rivers Foundation: 809 W. Riordan Rd. Suite 100-306, Flagstaff, AZ 86001. www.workingforrivers.org.

James Diebold and Robb Walt: Community Power Corporation: 8110 Shaffer Pkwy. Suite 120, Littleton, CO 80127 www.gocpc.com.
