

Soil Quality of a Semi-Arid Pasture Irrigated with Reverse Osmosis Wastewater—A Case Study from Northern New Mexico

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Abstract

Soil quality indicators were assessed in two adjacent fields in northern New Mexico near a reverse osmosis (RO) facility. One field had been cleared of native vegetation, sowed with a pasture mix and irrigated with saline RO wastewater (electrical conductivity (EC) of 2.73 dS/m) (WW) for two years. An adjacent field of non-irrigated, undisturbed native vegetation (NV) that received only natural rainfall was sampled for comparison and assumed to be representative of baseline values. Measurements included mean weight diameter (MWD), dry aggregates > 2 mm ($D > 2$ mm), dry aggregates < 0.25 mm ($D < 0.25$ mm), wet aggregate stability, permanganate oxidizable carbon (POXC), soil organic matter, EC, pH, sand, silt and clay contents, and chemical parameters ($\text{NO}_3\text{-N}$, P, Ca, Mg, Na, Zn, Fe, Mn and Cu). The wastewater irrigated field had more favorable soil quality indicators than the non-irrigated field, presumably due to the pasture mix and irrigation. However, the EC is higher in the WW irrigated field and will affect long-term utilization of the land for cropping, unless good soil salinity management is implemented.

Keywords

Soil Quality, Salinity, Total Dissolved Solids, Grassland

1. Introduction

The oil and gas industry in northwest New Mexico (NM) uses ultrapure reverse osmosis (RO) water to cool

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compressor systems. Reverse osmosis technology applies high osmotic pressure to push water through a semi-permeable membrane while excluding salts. Large-scale RO plants generate significant amounts of saline reject water or concentrate, which are typically returned to the waste stream for disposal. This wastewater has been shown to contain a variety of dissolved salts and other chemicals [1].

Water availability in the southwestern United States is limiting and has become a major constraint for agricultural production and sustainability [2]. With recurrent drought in an area like northwest NM that receives on average only 207 mm of precipitation annually [3], optimization of water resources including the utilization of wastewater for crop or rangeland production is imperative [4]. While wastewater application to crops and rangeland is attractive both as a means of disposal as well as a way to supplement rainfall, there are potential problems associated with the quality of water and the crop management strategy. There are concerns that using RO wastewater for irrigation purposes might lead to long-term salinity build-up in the soil and in the ground water system [1] [5]. In Oman and United Arab Emirates, where non-saline water is scarce and large-scale inland RO plants are used for the production of potable water, Ahmed *et al.* [6] proposed RO wastewater for use in brine shrimp production and for raising salt tolerant plant species, provided that the soil and ground water quality were not undermined.

Apart from the potential salinity hazard, the impact of the RO wastewater on multiple soil quality indicators needs to be assessed if such water is to be used for agricultural production. Most of the soils in semi-arid ecosystems have very low soil organic matter [7]. With the introduction of irrigation water coupled with appropriate vegetation, it may be possible to raise the soil organic matter content of these soils, thus increasing their productivity and quality. Water is a major constraint to organic matter accumulation in arid region soils [8]. Mohammad Rusan *et al.* [9] found that long term municipal wastewater application in a semi-arid environment led to increased soil salinity; however, the organic matter and plant nutrients also increased in the soil. They concluded that proper management of wastewater irrigation and periodic monitoring of soil fertility and quality parameters were essential to ensure sustainable use of wastewater for crop irrigation.

Several studies have reported the possibility of using saline irrigation water for crop production without adverse yield penalties [9]-[11]. In many of these studies, the key to long term utilization of saline water is dependent on appropriate irrigation water management, which may involve the alternate use of saline and good quality water or mixing of saline and good quality water. One of the keys to good water management is understanding the nature and properties of the soil under irrigation.

Case Presentation

In an attempt to utilize RO wastewater for beneficial agricultural use, RO plant operators in Aztec, NM (about 1700 m elevation; Lat. 36.828524, Long. -107.994976) cleared about 0.2 ha of native vegetation, tilled, sowed a dry pasture mix (“Hycrest” crested wheatgrass [*Agropyron cristatum* × *desertorum*], intermediate wheatgrass [*Thinopyrum intermedium*], Lincoln smooth brome grass [*Bromus inermis* Leyss.], Russian wildrye [*Psathyrostachys juncea*], dryland alfalfa [*Medicago sativa* L.], and “Pauite” orchard grass [*Dactylis glomerata* L.]) and irrigated with reject wastewater released from the adjoining RO plant. The reject wastewater was discharged through 15.2 cm gated pipe onto the WW land for 2010 and 2011 growing seasons (approximately May through Oct) at a rate of about 12.7 mm/week.

At the end of the two year period, the plant operators were contemplating converting the land receiving RO wastewater to vegetable crops and they requested technical assistance from NMSU. Site visits indicated what appeared to be visual symptoms of salt-impacted soil and a review of the previous agricultural practices prompted concern. Reject water chemistry reports provided by the plant operators confirmed high soluble salt content in the water being applied to the field (Table 1). Extension and research faculty advised the RO plant to cease land application of RO wastewater and proposed an assessment of the field to determine future best management practices and alternative land-use strategies. Adjacent to the RO wastewater land application site (WW) was a 0.2 ha field of non-cultivated native vegetation (NV) that had not received any supplemental water beyond the natural precipitation (Figure 1).

While not an intentional planned experiment, the site assessment represented an opportunity for us to evaluate the short-term impact of agricultural land application of reverse osmosis water on several soil quality parameters. The undisturbed, unirrigated field allowed a comparison of the RO-irrigated and unirrigated sites (e.g. for soil salinity and soil quality determinations). The ultimate goal of this case study was to present a strategy to RO plant managers seeking beneficial agricultural use of RO wastewater applied for crop or pasture production.



Figure 1. Aerial view of reverse osmosis (RO) plant and field (right) receiving the application of RO reject waste water (WW) and adjoining un-cultivated field of native vegetation (NV) used for comparative purposes.

Table 1. Quality of the reverse osmosis wastewater used for irrigation. Chemistry analysis conducted by Envirotec Labs (Farmington, NM) following USEPA and Hach Co. Methods.

Parameter (units)	Result
pH ^z	7.33
Electrical conductivity ^y (dS/m)	2.73
Total dissolved solids ^x @ 180°C (mg/L)	1390
Total dissolved solids ^w (Calc) (mg/L)	1690
Sodium adsorption ratio ^v	9.1
Total alkalinity as CaCO ₃ ^u (mg/L)	408
Total hardness as CaCO ₃ ^u (mg/L)	388
Bicarbonate as HCO ₃ ^u (mg/L)	408
Carbonate as CO ₃ ^u (mg/L)	<0.1
Hydroxide as OH ^u (mg/L)	<0.1
Nitrate nitrogen ^t (mg/L)	0.902
Nitrite nitrogen ^t (mg/L)	0.004
Chloride ^t (mg/L)	203
Fluoride ^t (mg/L)	0.713
Phosphate ^t (mg/L)	0.395
Sulfate ^t (mg/L)	637
Iron ^v (mg/L)	0.018
Calcium ^v (mg/L)	121
Magnesium ^v (mg/L)	20.9
Potassium ^v (mg/L)	4.98
Sodium ^v (mg/L)	411

^zUSEPA Method 9045 D; ^yUSEPA Method 6010; ^xUSEPA Method 120.1; ^uHACH Method 8203; ^sUSEPA Method 160.1; ^tUSEPA Method 300; ^wUSEPA Method 2540 C.

2. Materials and Methods

The soils of both WW and NV fields belong to the same mapping unit—Blancot Series, classified as Mesic Ustic Haplargids according to USDA soil classification [12]. The mean annual rainfall of the case study site is about 270 mm, while the annual average high and low temperatures are 20°C and 3°C respectively (measured at a weather station located at nearby Aztec National Monument [Elev.: 1720.291 m, Lat. 36.835, Long. -108.001]).

Soil Sampling

To compare the changes in soil quality indicators (SQI) due to RO wastewater application, 42 samples from 0 - 0.20 m soil depth were collected from each of the WW and the NV fields on a 63.7 m × 198.4 m grid laid out using a transit-level.

Physical soil measurements included the dry aggregate size distributions using a Ro-Tap sieve shaker [13]. For dry aggregate size distribution, air-dried soil was initially passed through an 8 mm sieve after which 500 g of soil was weighed out and carefully spread on top of a 4 mm sieve. The 4 mm sieve was then stacked on top of concentric sieves of following sizes: 2 mm; 1.4 mm; 1 mm; 0.5 mm; and 0.25 mm. A bottom pan collected particles/aggregates < 0.25 mm. The stacked sieves were positioned carefully on the Ro-tap shaker device and allowed to go through 5 minutes of shaking (278 oscillations/min and 150 taps/min). After shaking, the fractions left on each sieve were removed and weighed. Initial gravimetric moisture content (MC) of the soil was measured and the MC values were used to correct for the initial weight of the soil samples. Three parameters were computed from the dry aggregate size distribution measurement, including aggregates > 2 mm (fraction of soil remaining on 2 mm and 4 mm sieves) [AGG > 2 mm], aggregates < 0.25 mm (fraction of soil collected in the bottom pan) [AGG < 0.25 mm] and the mean Weight Diameter (MWD) calculated by Equation (1).

$$\text{MWD} = \sum x_i (w_i/W) \quad (1)$$

$i = 1;$

x_i = average diameter of a size class;

w_i = weight of aggregates in a size class of average diameter x_i ;

W = total weight of sample;

MWD unit is in millimeter.

Wet aggregate stability (WAS) was measured using the Cornell portable sprinkle infiltrometer [14]. Air-dried aggregates (2 - 4 mm) were placed on 2 mm sieve and a simulated rainfall of 2.5 J of energy was applied for 300 s on the aggregates. After the simulated rainfall application, the percentage of aggregates remaining on 2 mm sieve after correcting for particles > 2 mm was regarded as WAS.

Soil used for textural and chemical analyses was air dried in the laboratory and passed through a 2 mm sieve. Textural and chemical analyses were conducted on the soil fraction ≤ 2 mm.

Soil texture was determined using the hydrometer method [15]. Permanganate oxidizable carbon (POXC) was assessed using the technique developed by Weil *et al.* [16].

Soil organic matter was measured using Walkley-Black method [17]. Soil electrical conductivity (EC) and soil pH were measured on saturated paste extracts [18]. Soil phosphate-P and the micronutrients Zn, Fe, Mn and Cu were extracted with ammonium bicarbonate-DTPA [19] and analyzed by Inductively Coupled Plasma-Optical Emission Spectroscopy. Plant available Ca, Mg, and Na were all extracted with ammonium acetate at pH 7 [20]. Nitrate-N was extracted with 1 M KCl [21] and quantified using a cadmium-copper reduction column (Lachat Instruments, Milwaukee, WI).

Water quality analysis of the RO wastewater was conducted by a commercial lab (Envirotech Labs, Farmington, NM) according to the standards and methods developed by the United States Environmental Protection Agency [22] including Methods 9045 D (pH), 120.1 (conductivity), 160.1 and 2540C (TDS), 300 (anions), 6010 (cations) and Hach Method 8203 (alkalinity) Specific water measurements are listed in **Table 1**.

Soil measurements were compared between the WW and the NV treatments using independent sample t-test.

3. Results and Discussion

The quality of the RO irrigation water was assessed according to the standards developed by Ayers and Westcot [23] in which quality was classified according the degree of restriction on use. Three classes were identified

which included no restriction, slight to moderate restriction and severe restriction. Potential irrigation problems that were classified included salinity, water infiltration, specific ion toxicity, miscellaneous effects (NO₃-N and bicarbonates) and pH [23]. The EC and total dissolved solids of the RO wastewater was in the slight to moderate restriction class for salinity (Table 1). For the assessment of the water infiltration, SAR and EC of the irrigation water were combined to define the level of restriction. The RO wastewater quality does not pose any restriction to the soil water infiltration (Table 1). For the specific ion toxicity, sodium was in the severe restriction class whereas chloride was in the slight to moderate restriction class (Table 1). This implies the need to select crops that are tolerant to sodium and chloride toxicity for a successful crop production in the WW land. The NO₃-N level was in no restriction class while bicarbonate was in the slight to moderate restriction class. The pH of the irrigation water was in the normal range and represents no restrictions (Table 1).

There were significant differences in SQI between the WW and the NV fields including EC, POXC, AGG > 2 mm, AGG < 0.25 mm, MWD, silt content, K, Ca, Mg, and Zn (Table 2). Electrical conductivity measures the degree of salinity in the soil. The average EC of the WW soil (1.65 dS/m) was about three times higher than that of the NV soil (0.56 dS/m) (Table 2). Assuming that both fields had a similar initial EC of 0.56 dS/m, the RO wastewater irrigation would have contributed to higher salinity on the WW field within two years of wastewater application at an estimated rate of 0.55 dS/m⁻¹·y⁻¹.

Apart from the undesirable EC increase in the WW soil, other SQIs were more favorable in the WW soil compared to the NV soil. The POXC measures the amount of labile carbon pool in the soil [24] and this measurement

Table 2. Mean soil measurements in the wastewater irrigated field (WW) and the comparison field of native vegetation (NV) with one-way analysis of variance (t-test values), P values, and levels of significance (LS).

Soil property	WW	NV	t-value	P	LS
Electrical conductivity (dS/m)	1.65	0.56	4.25	<0.001	**
pH	8.22	8.19	0.53	0.572	ns
Permanganate oxidizable carbon (mg/kg)	380	346	3.99	<0.001	**
Soil organic matter (%)	0.73	0.78	0.57	0.571	ns
Wet aggregate stability (%)	58.91	62.66	1.80	0.076	ns
Aggregates > 2 mm (%)	13.1	4.9	4.68	<0.001	**
Aggregates < 0.25 mm (%)	28.6	39.6	5.70	<0.001	**
Mean weight diameter (mm)	1.008	0.606	4.99	<0.001	**
Sand content (%)	68.86	71.24	1.54	0.129	ns
Silt content (%)	6.24	4.83	2.89	0.005	**
Clay content (%)	24.90	23.94	0.65	0.517	ns
Nitrate nitrogen concentration (mg/kg)	1.33	0.67	1.76	0.0822	ns
Extractable phosphorus (mg/kg)	1.82	2.16	0.90	0.373	ns
Extractable potassium (mg/kg)	224	160	4.20	<0.001	**
Calcium concentration (mg/kg)	3496	2665	3.32	0.001	**
Magnesium concentration (mg/kg)	295	243	3.15	0.002	**
Sodium concentration (mg/kg)	110.61	97.90	0.40	0.689	ns
Zinc concentration (mg/kg)	1.14	0.90	2.22	0.030	*
Iron concentration (mg/kg)	6.90	5.71	1.54	0.129	ns
Manganese concentration (mg/kg)	4.64	4.52	0.24	0.810	ns
Copper concentration (mg/kg)	1.38	1.19	1.99	0.051	ns

**Statistical significance at 1% level; *Statistical significance at 5% level; ns: no statistical significant difference.

is well correlated with several other SQI such as basal respiration, substrate-induced respiration, microbial biomass carbon, soluble carbohydrate, soil organic carbon, and particulate organic carbon [16] [24] [25]. It has also been demonstrated that the POXC is a very sensitive SQI to changes in management [16] [24]. Therefore, POXC is not only an indicator for monitoring changes in the soil carbon; it is also a good indicator of microbial activity, nutrient cycling and availability in the soil. The POXC of the WW soil was about 10% higher than the NV soil (**Table 2**). This difference was significant at $<0.001\%$ (**Table 2**), and may indicate that the labile organic matter content of the WW soil had increased compared to the NV soil. This confirms the sensitivity of the POXC to changes in soil management compared to the total soil organic matter which showed no significant difference between treatments in this study (**Table 2**).

The extra water applied to the WW soil, even if marginal in quality, and the dry pasture seed mix probably led to more vegetation growth and this may have significantly affected the soil microbial functions and processes. This is a positive contribution from irrigation with RO wastewater, since it appears to have resulted in increased labile organic matter content. It is worth noting that this higher POXC was achieved with only minimal disturbance to the soil during initial tillage to establish the dry pasture mix. The increase in the POXC may have been lower or negated if there had been more tillage or disturbance to the soil. Tillage has been shown to lead to relative reduction in the soil organic carbon pools [26]. If the WW field is to be used for vegetable production, sustainable cropping practices may be necessary to increase and sustain the soil organic carbon pools. Practices such as minimum tillage, crop rotation and cover cropping will help sustain and build-up the soil organic carbon in WW soil.

The dry aggregate size distribution is an indicator of soil's susceptibility to erosion, particularly wind erosion. The $AGG > 2$ mm are large aggregates that will resist erosion while the $AGG < 0.25$ mm are small aggregates that are easily eroded. Previous studies have defined the soil fraction < 0.84 mm as an indicator of wind erodibility [27] [28]. It is desirable to have more $AGG > 2$ mm and less $AGG < 0.25$ mm for better soil quality. The MWD integrates all the aggregates collected on various sieve fractions into a composite index. The higher this index, the better the soil will be able to resist erosion. The WW soil had 2.7 times more $AGG > 2$ mm compared to the NV soil, while the NV soil had 1.4 times more $AGG < 0.25$ mm compared to the WW soil (**Table 2**). The MWD was also 1.7 times higher in the WW soil compared to the NV soil (**Table 2**). This suggests that wastewater irrigation of dry pasture vegetation may improve aggregation in arid and semi-arid soils, at least in the short term.

A higher MWD implies that the WW soil will be able to withstand erosive forces better than the NV soil. Wind erodibility is of particular importance in the study area, due to highly erosive winds that occur in the spring. The ability of the soil to withstand detachment and transport of sediments, together with appropriate surface cover such as the dry pasture mix will protect the land from soil loss and quality degradation.

The improvement in soil aggregation in the WW irrigated field may have been due to multiple reasons: i) increased labile carbon pools as shown by the higher POXC (**Table 2**) in the WW soil may have led to better aggregation through the increased activities of the soil microbes. Several studies have demonstrated the effect of the soil organic carbon pools and microbial activities on soil aggregation [29] [30]. Generally, soils containing more organic carbon tend to be better aggregated. WW soil had significantly higher Ca content than the NV soil. The Ca content of the wastewater (**Table 1**) may have contributed to Ca accumulation in the WW soil. Calcium has been associated with increased soil aggregate stability [31] [32]. Calcium-organic matter complexes have also been found to promote soil aggregate stability [32]. It is possible that the higher level of labile carbon may have interacted with the higher levels of calcium to promote better aggregation in the WW soil. Though the dry aggregation parameters were significantly different between the two fields, the wet aggregate stability was not significantly different (**Table 2**).

The sand and the clay contents did not differ between the WW and the NV soils; however silt content was significantly higher in the WW irrigated soil (**Table 2**). The silt content in the WW irrigated soil (6.24%) and the NV soil (4.83%) does not appear to have any impact on soil quality but may affect infiltration and leaching rates that could be important for long term management strategies.

Of the macronutrients measured, K, Ca and Mg were significantly higher in the WW irrigated soil compared to the NV soil (**Table 2**). Potassium, Ca and Mg were 40%, 31%, and 21% higher, respectively, in the WW soil compared to the NV soil. The higher level of these macronutrients in the WW soil was most likely due to the addition of these elements through the wastewater application. Though the K level for the WW soil was higher than the NV soil, both fields had very high levels of K from a crop requirement point of view and would require

no supplementary K for cropping of these lands [33].

Both fields had similar, very low levels of P and NO₃-N (**Table 2**). Fertilizers containing both N and P would be needed for profitable crop production on either field, but particularly in the WW soil if vegetables are to be grown. Most of the micronutrients measured (Fe, Cu and Mn) did not vary much between the WW and NV soils (**Table 2**) and were all in the sufficient range for New Mexico soils [33]. Only zinc was significantly higher in WW soil at an adequate level (1.14 mg/kg) compared to NV soil (0.9 mg/kg), which was present at a moderate level [33].

From the results of this comparative case study, it appears that the application of RO wastewater and seeding the field with a pasture mix may have led to a general improvement in many of the SQIs in the WW soil. Under the conditions of this study, the only issue that would likely present a long term challenge is soil salinity. Salinity is a critical soil property in arid and semi-arid regions, where irrigation water used for crop production introduces salts to the soil. Elevated levels of salinity can severely impact the growth and yields of several crops [34] [35]. However, the sensitivity of crops varies, with some crops being more tolerant of higher salinity than others [36]. The soil salinity must be considered if the WW land is to be used for horticultural vegetable and fruit production, as originally intended by the RO plant operators responsible for discharging the wastewater on the land. Like many other crops, vegetable species are highly variable in their tolerance to salinity [37]. While some vegetable species like Asparagus (*Asparagus officinalis*) and zucchini (*C. pepo melopepo*) are relatively salt tolerant, others such as carrot (*Daucus carota*) and onions (*Allium cepa*) have low salt tolerance [36] [38]. In addition, there are also intra-cultivar variations in salinity tolerance for vegetables [37]. Fruit crops like grapes (*Vitis* species) are also sensitive to salinity [39].

For successful horticultural crop production on the WW irrigated land, a good selection of appropriate species or cultivars tolerant to local conditions, including salinity, is essential. In addition, management of salinity through leaching of excess salts is necessary to maintain the WW land in long term crop production. Through careful irrigation water management, it is possible to minimize the salt build-up within the rooting zone. For effective use of the WW land for crop production, periodic leaching of the WW soil with higher quality water may be necessary to prevent excess salt build-up in addition to growing salt tolerant crop species and cultivars.

Some strategies have been advanced for the management and the use of saline irrigation water for crop production [40]-[42]. Rhoades *et al.* [41] demonstrated that saline water which otherwise would be classified as unusable can be successfully used for crop production through careful management of irrigation water, soil and crop rotation. Cyclic use of high and low saline water can prevent a rapid build-up of salts in the soil. Rhoades *et al.* [41] also proposed that using high salinity and low salinity water separately presents a greater flexibility and opportunity for crop production and they found that this strategy was better than mixing the two water types. Rhoades [40] reported a rotation study in which cotton (high salt tolerant crop) was grown for two years followed by wheat which has medium salt tolerance and then alfalfa which has low salt tolerance. Saline water was used for the two years of cotton irrigation, but beginning with the wheat crop, high quality irrigation water was used until the transition into alfalfa. Wheat could withstand the initially higher soil salinity resulting from using the saline water for cotton irrigation, and during the time of wheat production, the good quality water was able to leach out the salts in time for establishing alfalfa which is more salt sensitive than both the wheat and cotton [40]. Results of his field evaluation showed that the wheat and alfalfa yields were not significantly different when either saline or non-saline water was used for the preceding cotton crop grown for two years [40]. The lint yield for the first year of cotton was not significantly different between the saline and non-saline irrigation treatments, but the second year of cotton proved problematic with stand establishment [40]. Better yield was obtained when the second year cotton was established with non-saline irrigation water after which saline water was applied to raise the cotton crop to maturity [40].

A strategy of crop rotation, in which species with different salt tolerance are staggered within the cropping systems, combined with cyclical application of saline and non-saline water could be developed for a vegetable system in the WW field. If non-saline water is unavailable, the field could be planted to a dry pasture mix and left fallow for a period of 2 to 10 y to allow natural precipitation to leach the salts below the root zone. Maintaining the cover crop would reduce wind and water erosion and allow organic matter to stabilize. Another potential strategy is to utilize the RO wastewater for non-crop purposes such as aquaponics/shrimp culture or for raising algae as biofuel feedstock.

This case study took advantage of a local company's land application of RO wastewater to document changes in SQIs in a semi-arid field. Despite a nearby unamended field covered in native vegetation being used for

comparison purposes, this approach, unfortunately, has limitations. Companies seeking disposal options of waste water to agricultural lands should involve research scientists earlier in the process if they hope to demonstrate changes brought about by management decisions.

4. Conclusions

Soil quality indicators on a field seeded to a dry pasture mix and irrigated with wastewater from an RO treatment plant in northwestern New Mexico were compared to an adjacent field with native vegetation and no supplemental irrigation. Results showed that many of the soil quality indicators measured were improved in the field that had RO wastewater applied, compared to the field without irrigation. The indicators showing improvement in the soil that had received wastewater included POXC, AGG > 2 mm, AGG < 0.25 mm, MWD, K, Ca, Mg, and Zn. However, the EC of the soil irrigated with wastewater was significantly higher than the non-irrigated land, presumably due to the salinity of the wastewater.

Despite the overall soil quality improvement measured in the wastewater irrigated land, the salinity build-up may act as a major crop production barrier in the long term. In order to use the RO wastewater to irrigate for crop production, good salinity management must be employed including periodic leaching of the land with good quality water and a flexible cropping system. Other possibilities for the utilizing RO wastewater include applications such as aquaponics/shrimp culture or algae production as biofuel feedstock.

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