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SAND2007-6242

Unlimited Release

Printed September 2007

Production of Biofuels Using Nonfresh Water Sources

Amy C. Sun and Marissa D. Reno

Prepared by
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Production of Algal-based Biofuel using Non-fresh Water Sources

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Abstract

The goal of this LDRD involves development of a system dynamics model to understand the interdependencies between water resource availability and water needs for production of biofuels. Specifically, this model focuses on availability and feasibility of non-traditional water sources from dairy wastewater, produced water from crude oil production and from coal-bed methane gas extraction for the production of algal-based biofuel. The conceptual simulation framework and historical data are based on two locales within New Mexico, the San Juan basin in the northwest and the Permian basin in the southeast, where oil and gas drilling have increased considerably in the last ten years. The overall water balance ignores both transportation options and water chemistry and is broken down by county level. The resulting model contains an algal growth module, a dairy module, an oil production module, and a gas production module. A user interface is also created for controlling the adjustable parameters in the model. Our preliminary investigation indicates a cyclical demand for non-fresh water due to the cyclical nature of algal biomass production and crop evapotranspiration. The wastewater from the dairy industry is not a feasible non-fresh water source because the agricultural water demand for cow's dry feed far exceeds the amount generated at the dairy. The uncertainty associated with the water demand for cow's dry matter intake is the greatest in this model. The oil- and gas-produced water, ignoring the quality, provides ample supply for water demand in algal biomass production. There remains work to address technical challenges associated with coupling the appropriate non-fresh water source to the local demand.

Acknowledgment

The authors would like to acknowledge helpful discussions with Victor Cabrera, Mike Hightower, Ron Pate, Phil Pohl, Aldo Zagonel, Geoff Klise, Allan Sattler, and Len Malczynski.

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Executive Summary

Global events in the Middle East, natural disasters in the US, and high gasoline prices have prompted the Department of Energy and other federal agencies to seek technologies to diversify our country's energy sources and reduce domestic energy consumption. In particular, research and development have intensified for achieving cost-effective biofuel production. Bio-inspired processes for producing transportation fuels vary greatly depending on the source of feedstock. This work focuses on system-dynamic modeling of algal-based production of biodiesel and its associated water demand.

While work has begun to study the technologies to engineer the feedstocks for biofuels, there has been little investigation into the water demands and availability to support the large-scale production of biofuels. Unlike past or existing analyses of life-cycle assessment or economic analyses of alternative fuel productions, this model assesses water demand and supply by coupling the algal biomass production to non-traditional water sources, which are themselves dependent upon the industries that produce them. While such coupling is conceptual thus far, this work enhances our understanding of the interplay amongst energy production, energy consumption, water production, and water consumption. The geographical location ideally suited for this concept is the state of New Mexico, where its climate and parts of its terrain are ideal for algal growth. More importantly, New Mexico has accelerated its dairy, oil, and gas industries due to growing domestic demands. These three industries together generate large amounts of waste or produced water that can potentially be recycled. This case study addresses the challenges facing our nation's arid western and southwestern regions where combined economic and population growth require innovative solutions towards resource management.

A model is built based on system dynamics approach using Powersim software. The model consists of an algal biomass production module, dairy production module, oil production module, and natural gas module specific to coal-bed methane (CBM) production. For algae and dairy sectors, there is a water balance between supply and demand while for oil and gas the modules track water generated during productions. Heterotrophic algae requires solar radiation for growth, which results in cyclical growth curve. Similarly, maintaining a medium for maximal oil production requires constant replacement of overgrown media with fresh water supply in order to maximize solar radiation and mixing. The water balance associated with a dairy operation is also tracked in the model. Daily drinking requirement for dairy cows, maintenance of dairy parlor, and water for irrigating cow pasture and dry feed constitute the overall consumptive use of water in dairy module.

The produced water from oil and gas wells are constructed by first defining a theoretical production curve for oil (or gas) and a corresponding water production curve over the lifespan of a single well. The volume of produced water is inversely proportional to the volume of oil produced within the life of an oil well. For a CBM well, on the other hand, the amount of produced water is high in the beginning to depressurize the coal seams and

gradually approaches zero as the well ages. The modules assume a homogeneous distribution of wells with a specified well density. The volume of water produced from the oil and gas drilling more than compensates the non-fresh water required for the algal biomass production. This shows the greatest potential for coupling algal biofuel production to produced water.

Relative to the energy sector, water produced from dairy will not be available for algal production because of non-fresh water demand for agricultural irrigation. If only half of cow's dry feed mix are produced in New Mexico, the water demand for growing feed crops alone will require all of non-fresh water sources as well as supplemental water.

While this work provides a basic analysis coupling biofuel production to various possible water resources, there is still work to be done to reach credible conclusions regarding the feasibility and economic impact of using non-fresh water. There are five specific areas that need to be added to the current model: the energy consumption for water pumping and transportation, conventional natural gas production, water treatment options, land acreage requirement, and completion of integrating detailed data that have been uncovered during this research.

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Nomenclature

ET_o	Reference evapotranspiration, mm/da
λ	Latent heat of vaporization, (2.45 MJ/kg)
R_s	Solar radiation, MJ/m ² d ⁻¹
T	Mean air temperature, Celsius
R_a	Extraterrestrial radiation defined from the latitude and the day of the year.
T_{max}	5-day running average maximum temperature in Celsius.
T_{min}	5-day running average minimum temperature in Celsius.
R_{algae}	Algal growth rate, gm/m ² /da
$H_{daylight}$	Hours of daylight
$UV_{NewMexico}$	Monthly solar radiation in New Mexico.
UV_{June}	Solar radiation in June.
UV_{Dec}	Solar radiation in December.
$F(t)$	Crude oil or gas production function, bbl/da/well or Mcf/da/well
$F'_{location}$	Time-independent total production of one oil or gas well over its lifespan, bbl/well or Mcf/well.
$F_{total, location}$	Time-independent total production of oil or gas in a specified location.
$W'_{location}$	Time-independent total produced water of one oil or gas well over its lifespan, bbl/well.
$W_{total, location}$	Time-independent total production of produced water in a specified location.
$A_{location}$	Area of a specified location, acres.
$f(location, age)$	Hypothetical functional form of a production function.
$\rho(location, age)$	Well density in a specified local and age.

1. Background

1.1 Introduction

Energy dependency, energy sustainability, and energy security have attracted considerable debate and press in recent years. The US gets approximately 66% of its crude oil and 15% of its natural gas from imports [1]. These high percentages make our country vulnerable to disruptions in the foreign supply chain. Growing energy demand from countries that are trying to modernize, such as China, also challenges the notion that there will be enough reserve to meet the growing demand. The growing concerns have prompted the Department of Energy to challenge its national laboratories, the academia, and industry to seek technical solutions for diversification of the nation's energy source, for efficient use of energy-intensive technologies, and for reduction of energy consumption [2].

Equally significant, concerns for domestic water availability, water quality, and water sustainability have been increasing in municipalities around the nation. New Mexico serves as a textbook example of the nation's growing concerns over water availability. Tales of water shortage and conflicts have inspired novel approaches towards water resource management [3]. There have already been a few municipalities turning to water treatment options for reuse due to dwindling surface and groundwater supplies [4].

In recent years, Sandia has built robust programs that explore advanced technical solutions for utilization of alternative/renewable energy and for water sustainability. It is recognized as a leader in addressing interdependencies between energy and water. This project leverages Sandia's advanced modeling approach in system dynamics to address the growing concerns of water implications in biofuel production [5]. Furthermore, this work is unique by addressing non-traditional water resources from New Mexico as an option to meet the demand for biofuel production, which is synergistic with some of existing projects seeking water reuse options [6,7].

Combined mild climate and intense solar exposure make parts of New Mexico ideal for open algal pond operations. As part of the Aquatic Species Program, the Outdoor Test Facility in Roswell, New Mexico offers extensive data on algal operation that have been utilized in this work [8]. Hence, studying viable water resources for supporting production of algal-based biofuel within New Mexico is suitable for this modeling exercise.

1.2 New Mexico Industries

New Mexico serves as an excellent location for this study due to its increasing importance in inland production of oil and gas as well as its increasing stake in dairy production. There are two regions important to the oil and gas industries in New Mexico: the San Juan basin in the northwest and the Permian basin in the southeast. Figure 1 shows the impacted counties for oil and gas industries. These two regions account for most of oil and gas revenues in the state, supporting more than 23,000 New Mexico citizens. As of October 2006, there were 21,222 active oil-producing wells, 25,848 active gas-producing wells, and 603 active salt water disposal wells. Between 2001 and 2005, 2,733 oil wells and 5,572 gas wells were added to the overall well population, and the regions are noted as the most active drilling area in the lower-48 states. During the same period, 30% to 33% of overall gas production come from coal-bed methane (CBM) wells [9].



Figure 1 – Map of New Mexico by county. The San Juan basin extends northbound into Colorado and southbound to San Juan and Rio Arriba county. The Permian basin stretches from western Texas to southeastern New Mexico. Dairy farms are also populated in southeastern New Mexico. Curry, Chaves, Eddy, Roosevelt, and Lea counties make up 77% of total milk cow population in New Mexico.

The San Juan basin is approximately bordered by the AZ-NM state line to the west, the San Juan Mountains (in Colorado) to the north, the Chaco slope to the south, and Brazos uplift to the east. Specifically, the coal-bed methane activities have yielded large

quantities of produced water that raised environmental concerns from local communities [10]. The approximate cost of creating re-injection wells for produced water disposal is about \$2 million each. Hence, disposal of produced water has been an integral part of coal-bed methane operation and cost equation in the region. More importantly, the quality of brackish water in the San Juan basin can vary from 300 mg/L total dissolved solid (TDS) to 25,000 mg/L TDS depending on the location of the well.

The oil and gas operations in southeastern New Mexico draw from the western portion of the Permian basin that crosses into western Texas. The basin is approximately 250 miles wide and 300 miles long and holds the largest oil reserve in the lower-48 states. Like natural gas operations, similar concerns are raised for disposal of produced water in oil production. Depending on the geological location of wells, the water quality of produced water varies considerably.

The dairy industry is another thriving operation in the southeastern part of New Mexico. Since the 1990s, this region has shifted its predominantly agricultural base to support dairy farms. Two of the world's largest cheese plants are located in Clovis and in Roswell [6]. While New Mexico ranks 7th in dairy production, its average herd size is the largest in the nation (~1500-2000 cows). For every pound of milk produced, there are 2-3 pounds of waste generated. Discounting the dry manure solids, the liquid waste can range from 3 to 15 millions gallons per day depending on the specific county. The quality of wastewater is poor due to the high nitrite content; however, unlike the briny quality of oil- and gas-produced water in New Mexico, most of the dairy wastewater may be reused to irrigate pasture [12-15].

This work examines the availability of non-fresh water from the oil, gas, and dairy industries as well as the water demand for algal biofuel production. While this work still falls short of an in-depth analysis of the water chemistry or energy consumption, its basic framework is easily extendable to include finer-resolution mass balance and economic analysis.

2. Model

2.1 Causal Loop Diagram

A conceptual diagram is created in VENSIM^R and illustrated in Figure 2 for this study. There are three types of stocks: mass, volume, and area. Mass accumulation originates from algal and cattle growth, which depends on the available resources such as sunlight, nutrients, cattle feed, and water. The volume stock tracks the water demand and supply for biomass and dairy demand. The area stock tracks land acreage available for various types of usage such as housing development or industries. The exogenous variables influencing the amount of cumulative stocks are also listed in Figure 2. The sign along each arrow shows the causal relation between two connecting entities. A positive sign reinforces the rate process (e.g. increasing sunlight increases algal growth) while the negative sign represents negative feedback in the process (e.g. increasing algal death decreases algal biomass).

Algal growth, for example, depends on the availability of sunlight, nutrient, and mixing in the ponds. If biomass accumulation is more aggressive than the rate of removal, the toxicity in the pond will increase, which can accelerate deaths. Hence, maintaining an optimal solid fraction is key to sustaining biomass production. Equally important, the increase in biomass increases shading in the pond, which impacts the amount of solar radiation to the growth medium. The other mass accumulator is related to growth of the cow population. The milk cow population in New Mexico has been growing sharply since the mid-1990s. This is due to an increase in dairy production in New Mexico. The dairy operation involves consumptive use of water for drinking, washing of the parlor, and irrigation. This model does not include an aging chain for the milk cows since it is assumed that large dairy operations rely on a separate supply chain for milk cows and maintain a fairly equilibrium population to supply dairy products year-round.

One of the outputs from the dairy operation is the wastewater that can potentially be reused elsewhere. The current dairy operation recycles its processed water by either using it for irrigating cow pasture or for parlor washing. Other sources of non-fresh water involve produced water during oil and gas production. The production of non-fresh water is directly dependent on oil or gas productions. More detailed descriptions will be given in the next few sections.

While the land sector is represented in Figure 2, it has not been explicitly modeled in this work. The population density in northwestern or southeastern New Mexico remains low, and the land available for algal growth does not necessarily compete with housing industry since it is more desirable to place algal ponds far away from municipalities. Due to the non-competitive nature of land usage in modeled regions, it is assumed that the dynamics associated with competing land use does not impact the outcome of water balance [17]. Nevertheless, it is necessary to obtain more details on land availability in the region before such a conclusion can be made.

The price variables have been noted in the causal loop diagram but not integrated into the conceptual model. While water, electricity, fuel, and land prices all impact productions of biofuel, crude oil, gas, and dairy, they are currently outside the scope of this study. Accounting for the price sensitivity would require effort beyond the limits of this current work. Another basic assumption of this work is co-location of algal biomass production and its potential non-fresh water sources, which minimizes the transportation requirement for water transport. Again, the model is extendable to consider a water transportation infrastructure and should be included in the future.

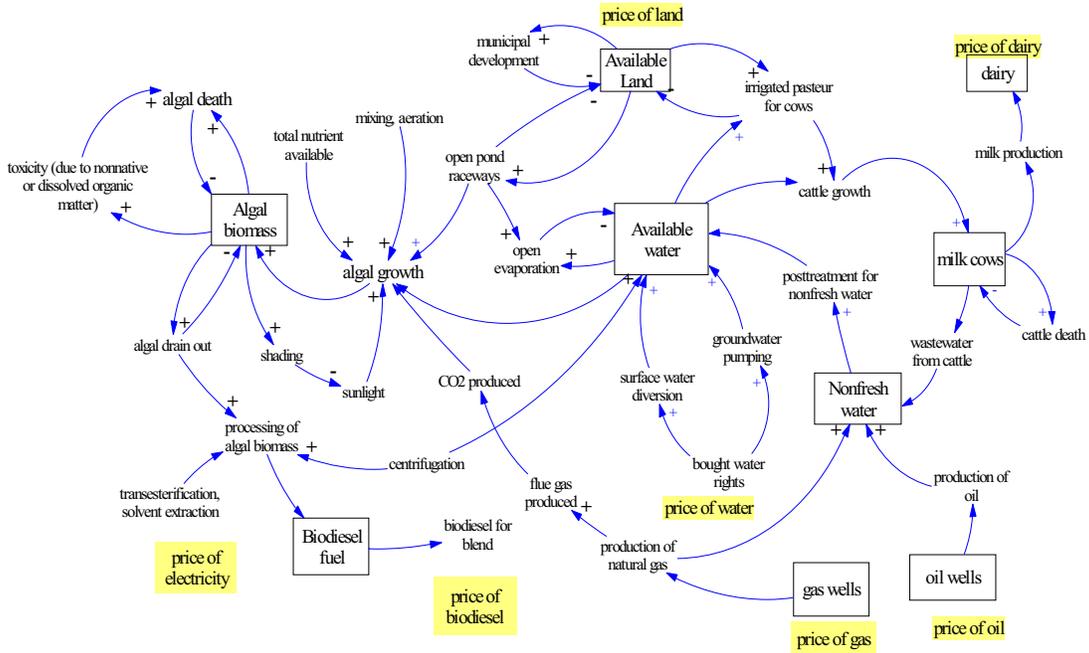


Figure 2. Causal loop diagram for Algal-based Biofuel production.

Based on the conceptual design of causal relationships, a more detailed system dynamics model is programmed using PowerSim Studio for each sector [18].

2.2 Algal production

Studies of algal biomass production as a means of green house gas mitigation and water remediation has been carried out in the last few decades. Concurrent production of biofuel and carbon dioxide mitigation has been studied extensively by Benemann in the 1990s [8]. Benemann's report concluded that the cost of such operation is still high relative to CO₂ mitigation goals, which varies between \$74/mtCO₂ fixed into oil to \$36/mtCO₂ fixed into oil as algal growth rate doubles from 30gm/m²/da to 60 gm/m²/da. This range translates to \$59/bbl and \$39/bbl. The technical challenge lies in harvesting algal biomass and extraction of biodiesel. Unlike extracting natural deposits of oil and gas, efficient biofuel production from algae requires expertise in aquaculture and process engineering. The heterogeneity of algal species and growth conditions makes this bio-inspired option a technical challenge for scale-up consideration. Furthermore, ideal algal growth conditions require optimal growth medium, which makes it a water intensive option.

The algal sector module based on system dynamics consists of a mass balance and a water balance. Each stock is formulated separately but the two balances are coupled due to the desired concentration required in order to maintain optimal growth. Figure 3 shows the user interface that one can adjust in the input. There are three types of controls set up for this module: one related to algal production system, one specific to the type of algal strain, and one related to downstream harvesting method. Based on any combination of choices, the module will calculate the net volume of water required to maintain ideal growth.

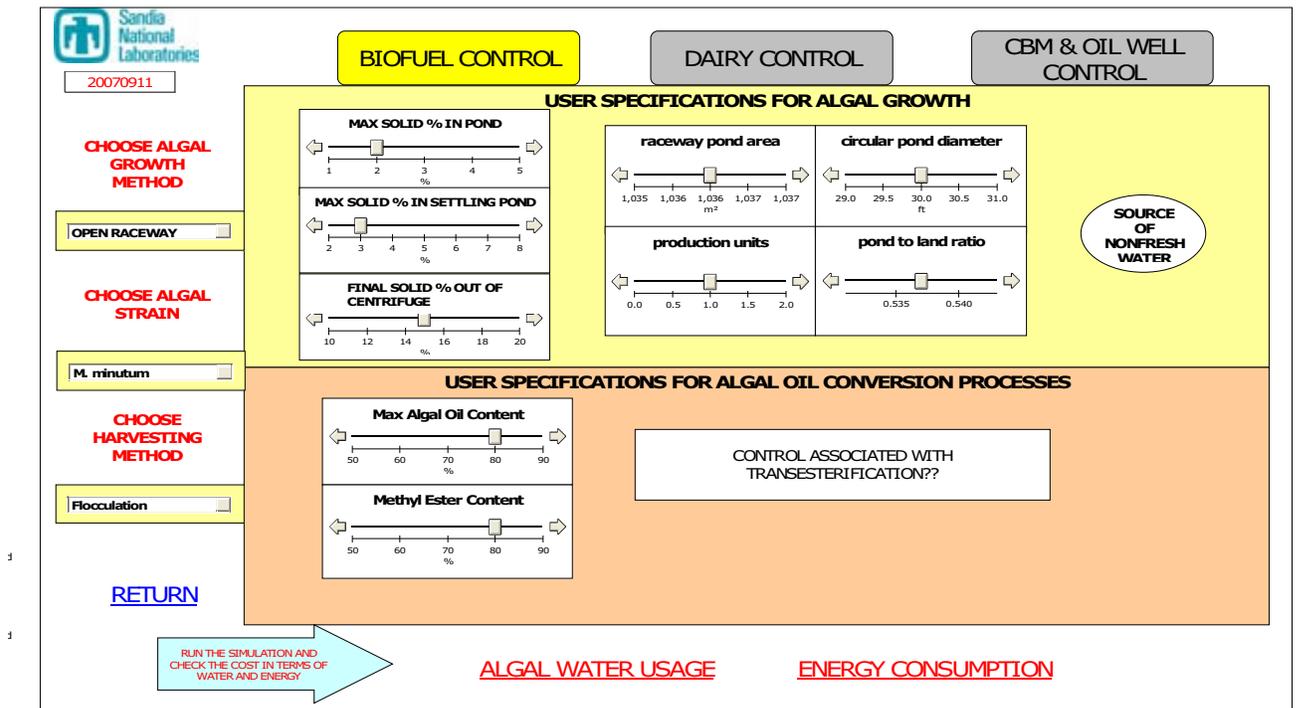


Figure 3 Sample of Biofuel User Control.

Figure 4a and Figure 4b show graphs based on open raceway design for growth of *M minutum* species. The model input parameters such as desired solid fractions, pond dimensions, and growth rates are derived from a thesis study using data from the Outdoor Test Facility in Roswell, New Mexico [19]. The growth curve shown in Figure 4a, based on seasonal variability of solar radiation in New Mexico, results in cyclic behavior of algal production. The algal growth to solar radiation relationship is linear assuming ideal growth conditions are maintained throughout.

$$R_{algae} = \frac{H_{daylight}}{24} (UV_{NewMexico} * 3.76 - 11.16) \quad (1)$$

$$UV_{NewMexico} = \frac{(UV_{June} - UV_{Dec})}{2} \sin\left(Day * \frac{\pi}{183} - \frac{\pi}{2}\right) + \frac{(UV_{Dec} + UV_{June})}{2} \quad (2)$$

R_{algae} is the growth rate in gm/m²/da, which is defined as a function of number of hours of daylight, $H_{daylight}$, and an averaged, monthly solar radiation in New Mexico, $UV_{NewMexico}$. The solar incident radiation is approximated by a sinusoidal function weighted by the solar radiations of the most and least sunny months.

Figure 4b summarizes the water balance based on a 1% solid fraction in the raceway ponds, 3% solid fraction in the settling ponds, and 15% solid fraction after centrifugation. Based on the concentration factors, 80% of water taken to the centrifuge returns back to the raceway after algae removal. Open evaporation from open raceway and settling ponds accounts for most of water loss year round. At maximal algal growth, open evaporation accounts for 68.6% of water loss. Once the net water need is calculated, the amount of non-fresh water required to maintain the algal operation is also determined.

It is the intent of the authors to continue this work to add energy costs associated with pumping and mixing of the various water streams. While the link has been created to view energy consumption, the graphs are currently unavailable.

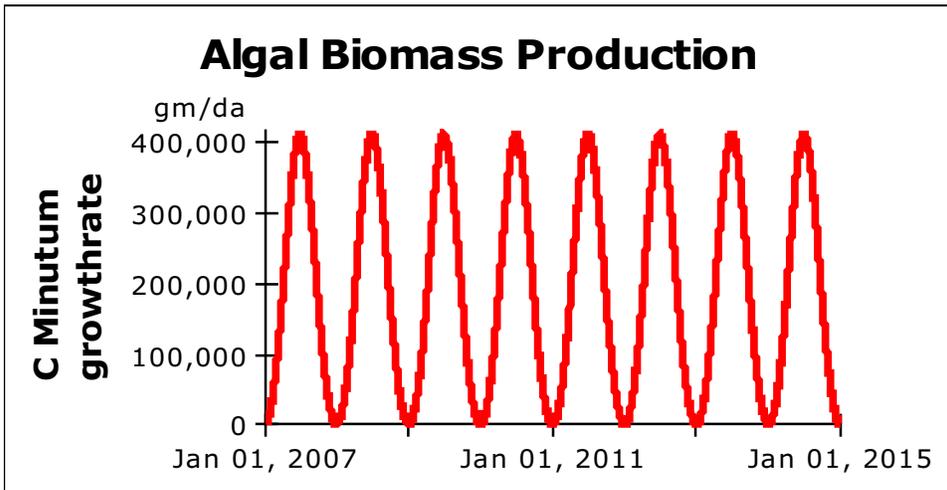


Figure 4a – *M minutum* Growth curve over 8 year cycle.

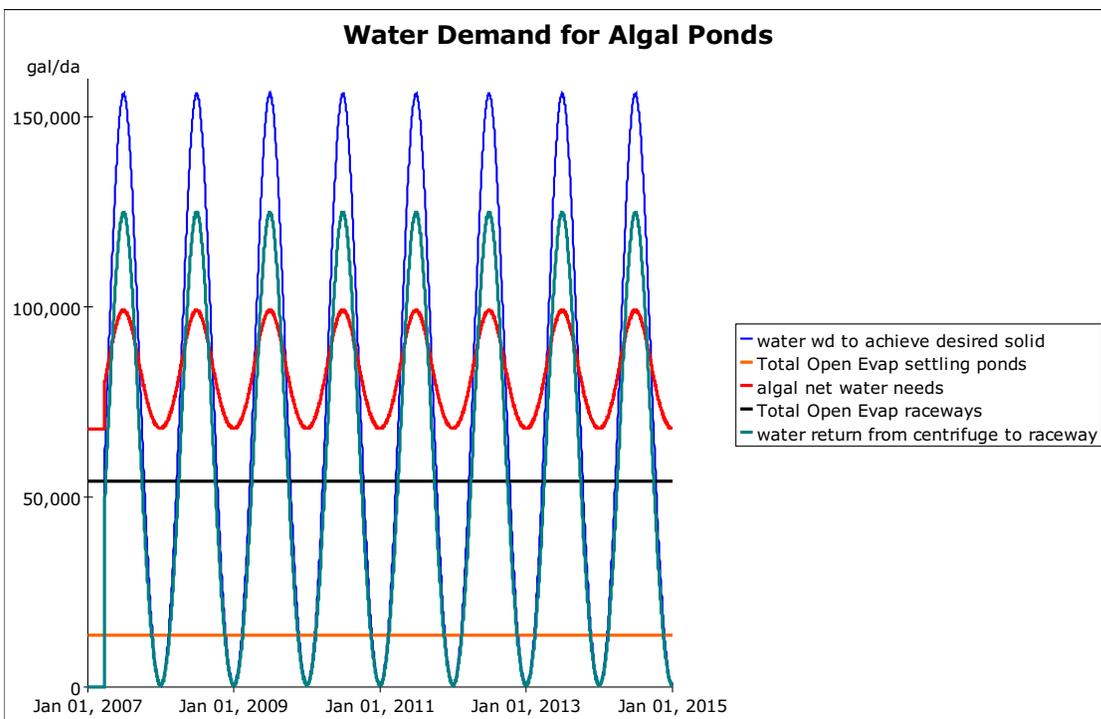


Figure 4b – Water Demand for Open Pond design and *M minutum*.

2.3 Dairy production

The dairy production module is created to track the water usage during milk production. There are three types of consumptive uses associated with the dairy operation: drinking water, process water to maintain cleanliness, and irrigation water for growth of cow feed. The volume for drinking and process water are by default set at 25 gal/da/head and 22 gal/da/head respectively. Of the 22 gal/da/head of process water, 40% of it is recycled back to the parlor [17]. These numbers, along with cattle population growth rates are all part of the user interface for the dairy module, as shown in Figure 5. It is assumed that the drinking water and non-recycled process water must be derived from a fresh water source, such as groundwater pumping. In the absence of a water treatment module for this model, it is assumed that the wastewater as well as processed water would not be potable for cows, nor appropriate for cleaning dairy processing units.

Since the growth of cattle population varies by county, the user is allowed to vary the growth rates manually or follow a historical trend. The historical growth trend is based on milk cow population data between 2000 and 2007 [20].

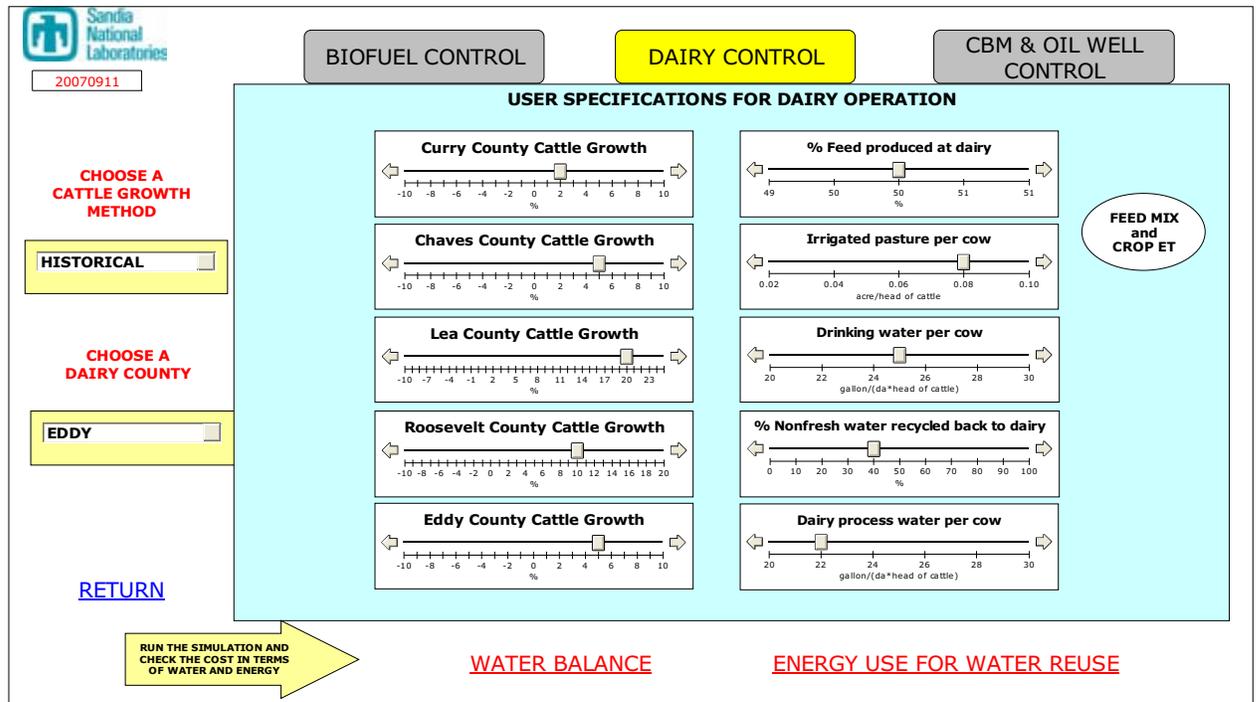


Figure 5. Dairy User Control Page.

Another set of controls that need to be addressed is related to the water budget associated with cattle feed. At the current time, it is unclear how much local agricultural activities support the dairy cows by providing the necessary dry feed mix; hence, the percentage of feed produced at dairy is an adjustable parameter in the model. By default, half of the dry feed mix is derived locally. This impacts the water requirement for growing the feed mix. The crop evapotranspiration is referenced against the Hargreaves equation [21]. The temperature data are based on historical daily average data at Navajo Dam, New Mexico [22].

$$ET_o = 0.0135 \frac{R_s}{\lambda} (T + 17.8) \quad (3)$$

$$R_s = 0.16R_a (T_{\max} - T_{\min})^{0.5} \quad (4)$$

where: ET_o = Reference evapotranspiration, mm/da
 λ = Latent heat of vaporization, (2.45 MJ/kg).
 R_s = Solar radiation, MJ/m² d⁻¹
 T = Mean air temperature, Celsius
 R_a = Extraterrestrial radiation defined from the latitude and the day of the year.
 T_{\max} = 5-day running average maximum temperature in Celsius.
 T_{\min} = 5-day running average minimum temperature in Celsius.

Another control is related to the area requirement for cattle. The default 0.08 acre/head is based on an average dairy farm acreage divided by its lot size. In the absence of an agricultural expert who specializes in cow feed mix in SE New Mexico, the make-up of a typical milk cow feed remains highly speculative in this model. There have been numerous references to the importance of forage-based feed mix in New Mexico for providing low-water use, high-value crop over seed-base feed mix [23]. The “Feed Mix & Crop ET” link from Figure 5 allows the user to change the make up of feed mix, as shown in Figure 6. A Harris slider bar, which is a relative proportionality slider construct that permits the weighted allocation of resources by percentage based upon their starting contributions to the total, allows the user to change the relative percentages of feed crops. A more detailed definition of the Harris slider bar is given in Appendix.

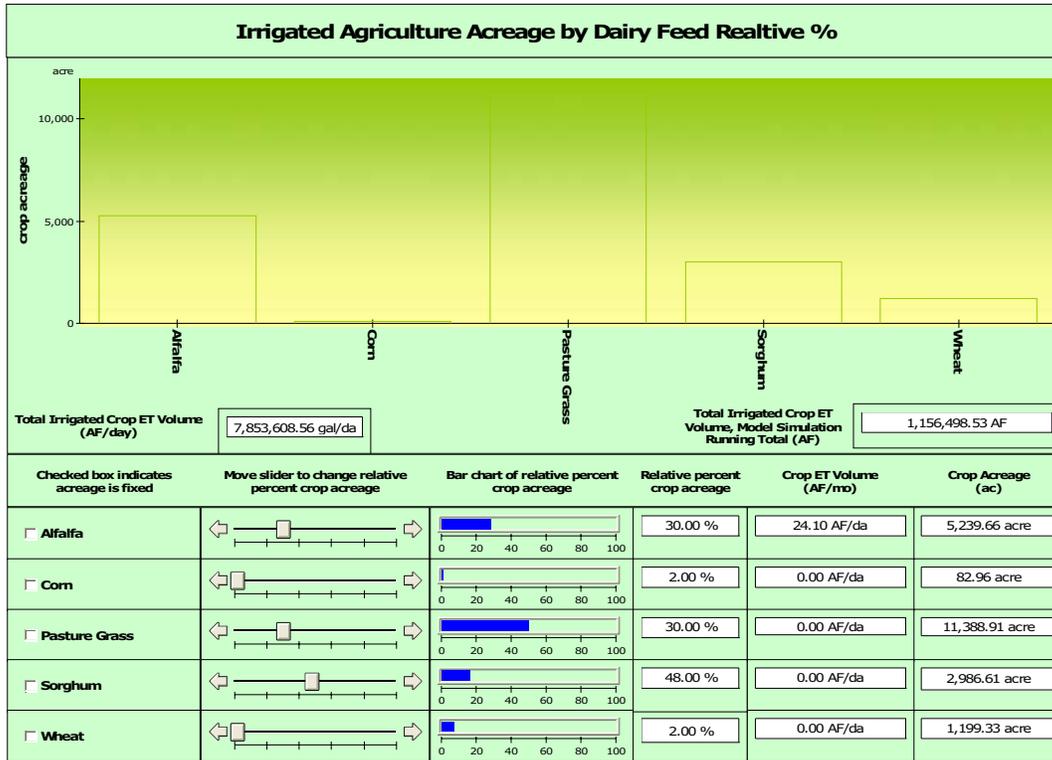


Figure 6. Harris slider bar for feed mix control.

Figures 7 shows the milk cow population trend in the next eight years in the five southeastern New Mexico counties. Figures 8a and 8b show the resulting water requirement for three types of usage as described above. As shown in Figure 8a, the evapotranspiration required by the feed crops overwhelms the other water usage in a dairy operation. Figure 8b shows more details of the non-ET consumptive use of water.

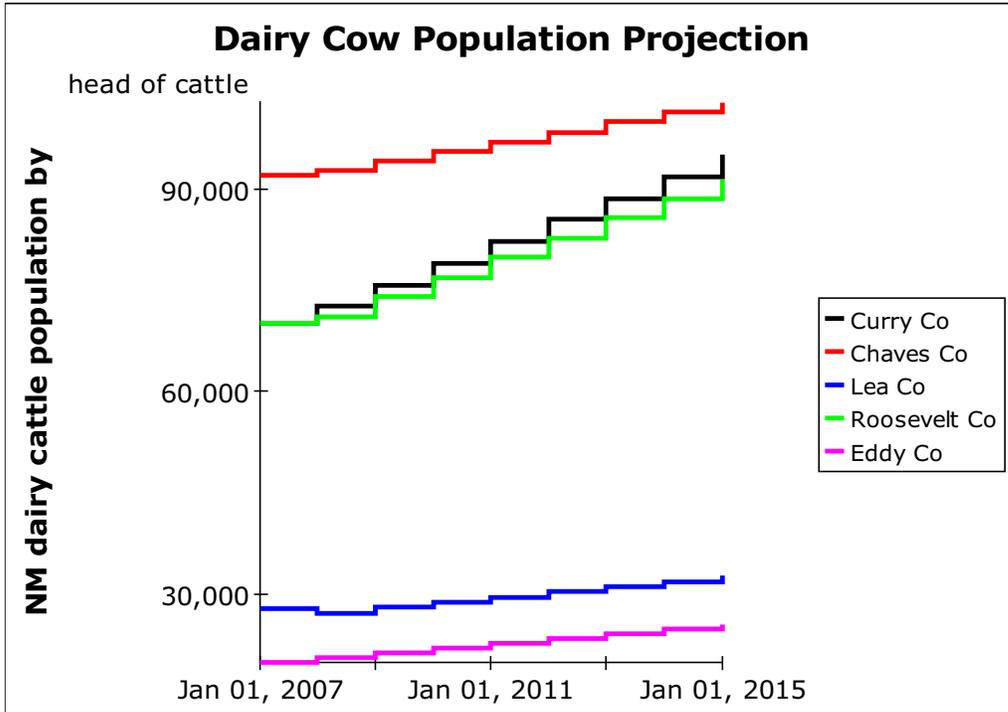


Figure 7. Milk Cow population projection from 2007 to 2015.

Again, the amount of water for irrigation is highly dependent on the type of crops and percentage of feed produced in New Mexico. The resulting amount of water loss through crop evapotranspiration is still highly speculative. Nevertheless, the accuracy of modeling the agricultural loop for feed mix is needed because it imposes the highest demand on water. The green curve plotted in Figure 8b represents the volume of wastewater generated from dairy operation in Curry county. The amount of potential wastewater cannot offset the demand from agricultural use. It is clear that it is essentially impossible to reuse dairy-based non-fresh water for other means despite its potential.

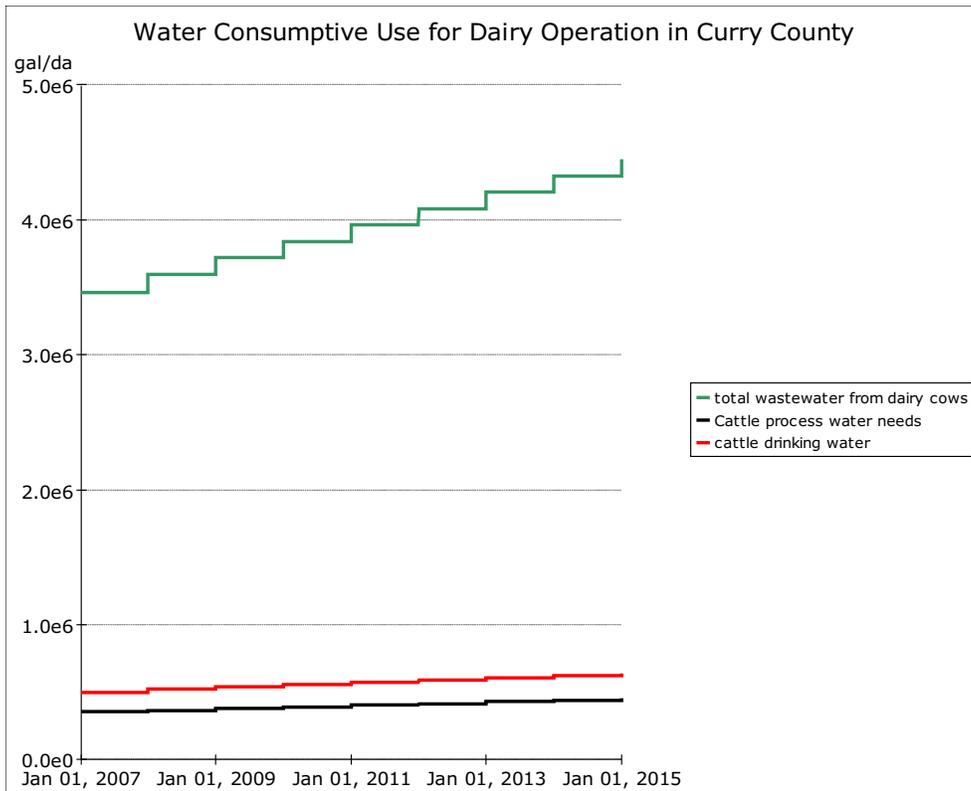
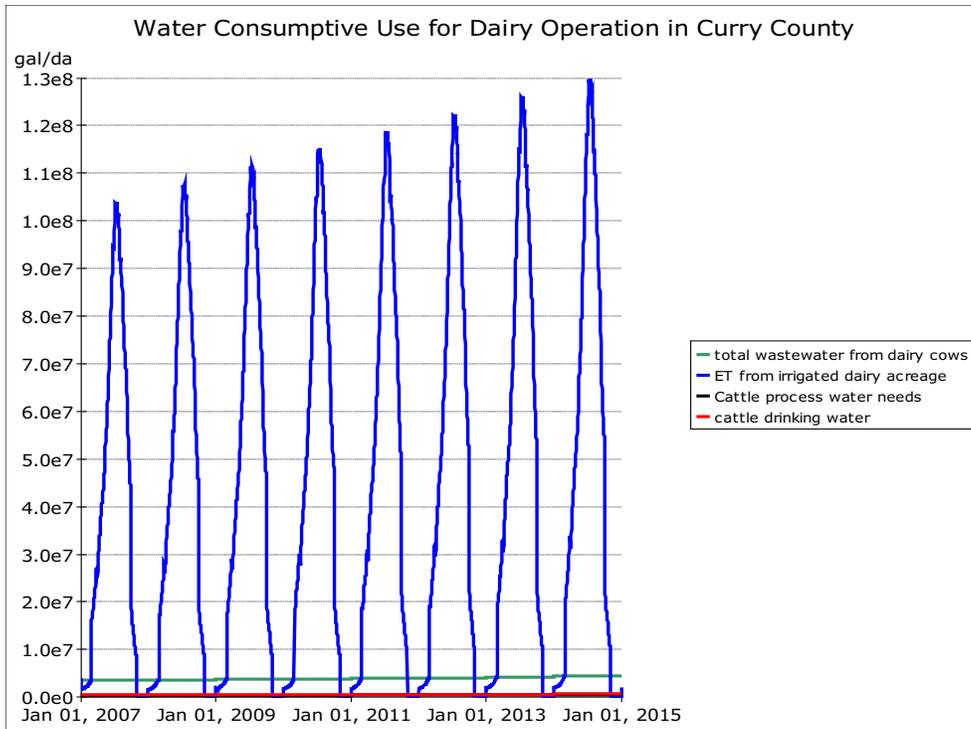


Figure 8a & 8b. Water demand for dairy cow drinking water (red), dairy cow process water (without recycle, black), and crop evapotranspiration (blue). The green curve shows the wastewater generated from dairy cows.

2.4 Oil and Natural Gas Modules

Oil and natural gas productions are defined and created in this model for the purpose of quantifying the volumes of non-fresh water extracted during the production processes. More importantly, it is well known that the volume of produced water is highly dependent on the age of wells in both fuel extraction processes. Two separate modules have been created for this section, one specific to oil production and the other specific to coal-bed methane production. More research is needed to add a module simulating traditional natural gas production and its corresponding produced water; hence, it does not exist in the current model.

For both oil and gas operations, the production level is a function of the age of wells and the location of well; i.e.,

$$F(t) = f(\text{location}, \text{age}) \quad (5)$$

$F(t)$ is a rate quantity such as barrels/day/well. The *age* is defined as the period of time since the well first comes on production, or $\text{age} = t - t_{\text{start}}$. The total production over the entire lifespan of a single well is the integral of the production function; i.e.,

$$F'_{\text{location}} = \int_{-\infty}^{\infty} F(t) dt = \int_0^{T_{\text{lifespan}}} f(\text{location}, \text{age}) dt, \quad (6)$$

where T_{lifespan} is the lifespan defined for a well. Both modules assume all wells of the same type have the same production lifespan, which is set at 8 years for a gas well and 70 years for an oil well. At any given time t , the production fields within each county are populated with wells of different ages. Hence, for a specific location, there is a well density function; i.e., $\rho(\text{location}, \text{age})$, and the total production level in a given area will be the integral of products ρ and f .

$$F_{\text{total}, \text{location}} = A_{\text{location}} \int_0^{T_{\text{lifespan}}} \rho(\text{location}, \text{age}) f(\text{location}, \text{age}) dt \quad (7)$$

A_{location} is the area of location of interest. For this model, the location is designated at a county level. For simplicity, this study assumes the well density to be independent of the age of wells. In other words, there is an equal probability of finding wells of any age at a given location. In terms of transient dynamics, there is also an equal number of new wells being added to the area as there are wells retiring, so the age distribution is always time independent. This assumption simplifies the integral by making the density term time independent.

$$F_{\text{total}, \text{county}} = A_{\text{county}} \rho_{\text{county}} F'_{\text{county}} \quad (8)$$

While the historical production data for oil and gas production show linear trends, the model uses an average annual production level for the entire year.

To obtain the volume of produced water for a given well, the fuel production function F' is replaced with a water production function W' .

$$W_{total, county} = A_{county} \rho_{county} W'_{county} \quad (9)$$

Figure 9a and 9b show schematic plots of $F(t)$ and $W(t)$ for oil and coal-bed methane. These plots are hypothetical and more work is required to obtain a more rigorous representation. Specifically, oil production is rich in oil and light on water when the well is young. As more drawdown occurs as well ages, the volume of water being extracted increases. The water to oil ratio can range from 5:1 to 100:1 (bbl water/bbl oil) [25].

On the other hand, produced water from CBM behaves opposite to that of oil-produced water. When the CBM well age is young, the amount of water extracted is high to depressurize the coal seam. The volume decreases rapidly as gas production level increases. The well densities and county areas are back calculated from State oil and gas production statistics [9].

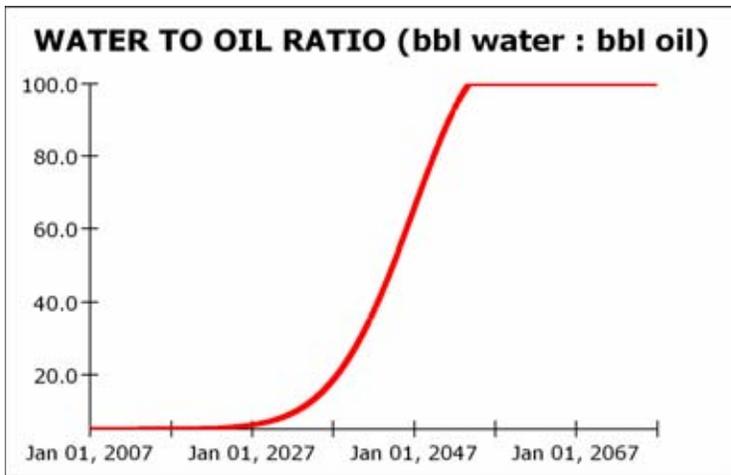
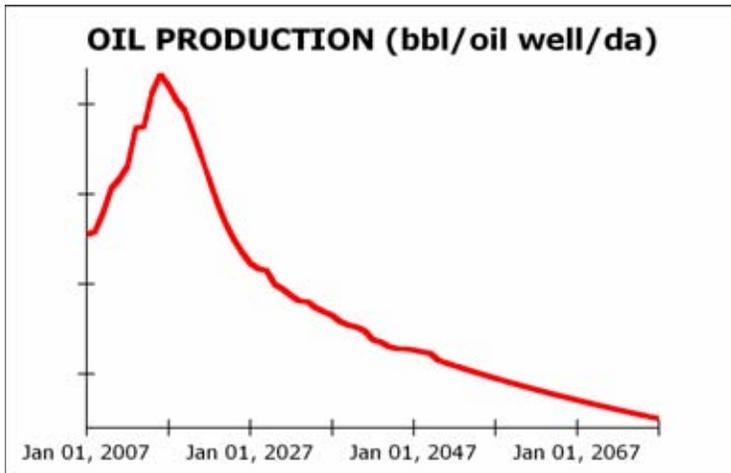


Figure 9a. Oil production curves. F is a theoretical production function and the water production function is plotted as water to oil ratio.

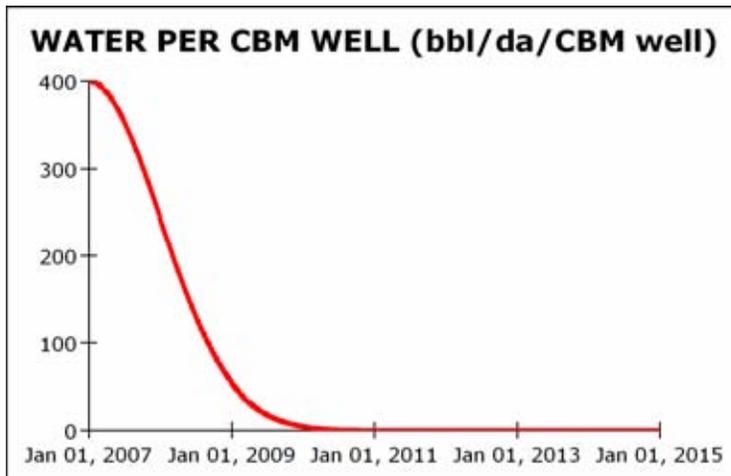
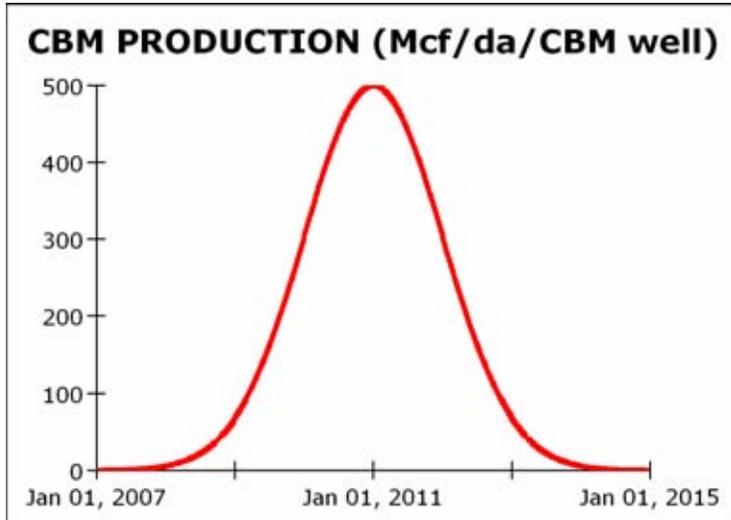


Figure 9b. CBM production curves. F is the production function and W is the water production function. The total amount of gas or water over the entire lifespan equals the area under each of these two curves.

Since oil and CBM production characteristics are specific to the well field, model users are allowed to change several variables, including maximum and minimum production rates and the well density for each county, as shown in Figure 10. There is a self consistency check on the choice of county. With the exception of Curry County, where only dairy operation exists, as well as San Juan and Rio Arriba counties, where only oil and gas operations exist, the choice of the rest of the southeastern New Mexico is consistent between “DAIRY Control” and “CBM&OIL WELL Control” page.

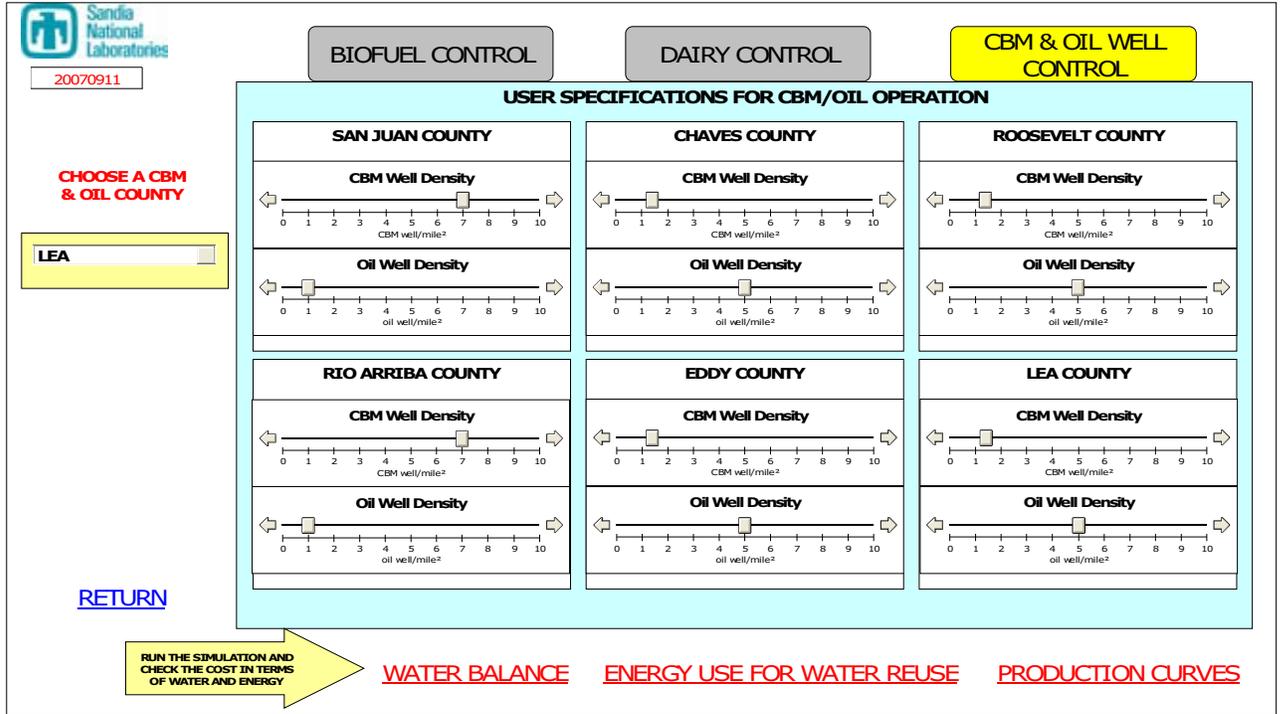


Figure 10. CBM and Oil Well Control.

2.4.1 Oil Production

Inadequate oil well location and age information currently exists, hence Equation (6) is not used to calculate oil production. Instead, monthly production data for the state of New Mexico are obtained for January 1981 to March 2007 [1] and fit using a second-degree polynomial. This equation is then used to project oil production to the end of the simulation period. Detail at the county level is resolved using percent of total production shares equal to 0.82%, 58.91%, 0.62%, 35.37%, 2.05%, and 2.09% for Chaves, Lea, Roosevelt, Eddy, San Juan, and Rio Arriba counties, respectively [9]. Figure 11a shows the production level as implemented in Powersim for the entire state of New Mexico and the two top-producing counties. Figure 11b shows the non-fresh water production associated with this level of oil production, which is calculated by multiplying these production functions (bbl oil/year) by the water to oil ratio function shown in Figure 9b (bbl water : bbl oil), giving bbl water/year. This non-fresh water is then treated as a potential source to the algal growth process.

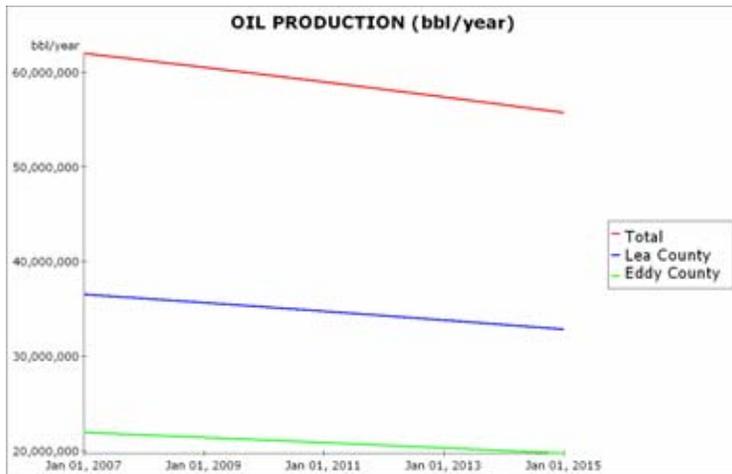


Figure 11a. Oil production curves for the state of New Mexico (red line) and the two top-producing counties (Lea, blue line; Eddy, green line).

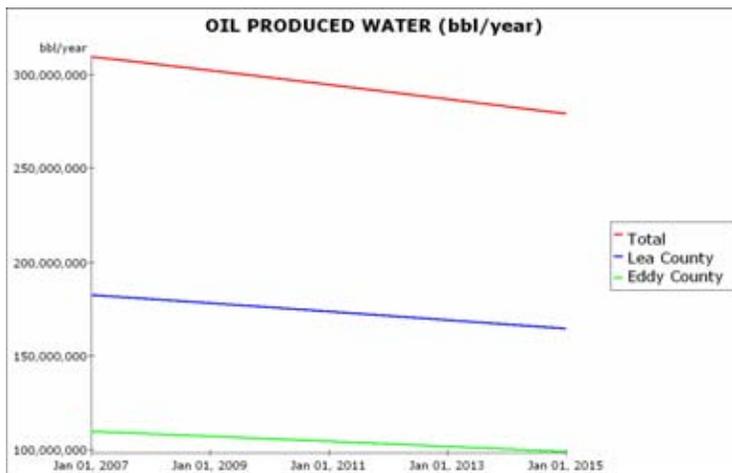


Figure 11b. Oil produced water curves for the state of New Mexico (red line) and the two top-producing counties (Lea, blue line; Eddy, green line).

2.4.2 Coal-bed Methane Production

Coal-bed methane production and the corresponding non-fresh water production are quantified using the method outlined in section 2.4. Using the per well CBM production function shown in Figure 9a for F'_{county} , $F'_{total, county}$ was calculated. Similarly, using the per well water production function shown in Figure 9a for W'_{county} , $W'_{total, county}$ was calculated. Figure 12a gives CBM production for the entire state of New Mexico and the two top-producing counties, while Figure 12b gives the non-fresh water produced as a result of the CBM gas extraction process. As with the oil-produced non-fresh water, this CBM-produced non-fresh water is also treated as a potential source to the algal growth process.

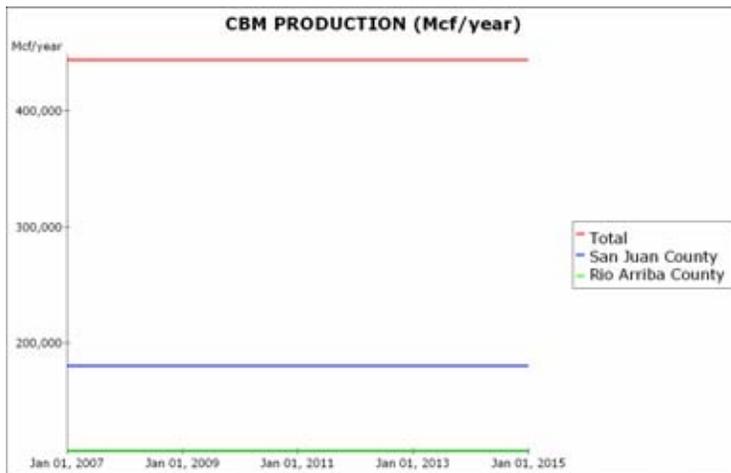


Figure 12a. Coal-bed methane production curves for the state of New Mexico (red line) and the two top-producing counties (San Juan, blue line; Rio Arriba, green line).

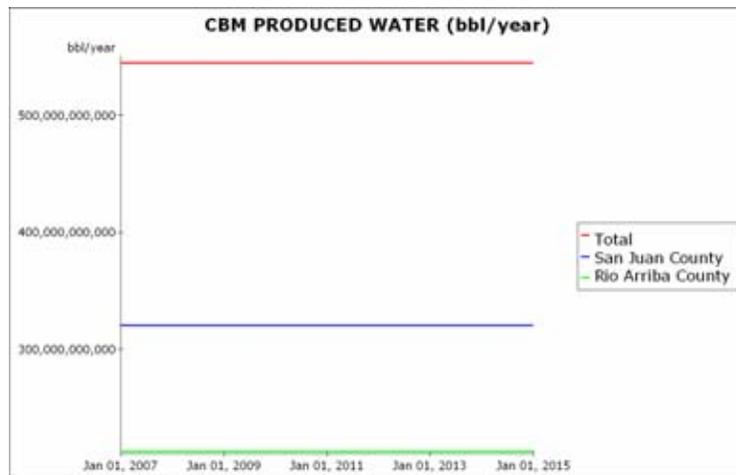
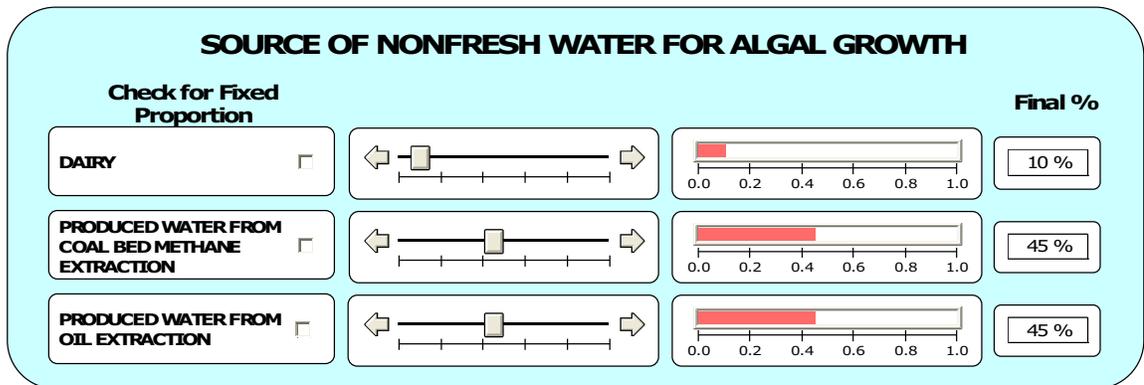


Figure 12b. Coal-bed methane produced water curves for the state of New Mexico (red line) and the two top-producing counties (San Juan, blue line; Rio Arriba, green line).

3. Discussion

Once each sector has been identified and properly modeled, the relative amount of non-fresh water source can be adjusted by the user, as shown in Figure 13.



[RETURN](#)

Figure 13 – Harris slider of the relative distribution of different non-fresh water source.

By default, the model sets the demand for produced water from oil and gas in equal quantity. Since the dairy sector requires more non-fresh water for crop evapotranspiration than for other interests, its percentage is set to 10%. Figure 14a shows the total water demand for fresh and non-fresh sources. The amount that is pumped from a groundwater source is the volume required for the sum of the dairy cows drinking water, dairy process water, and unmet demand for non-fresh water. The contribution from a non-fresh source can be as much as 50% of the total water demand. The distribution of non-fresh water usage is shown in Figure 14b. The amount of dairy wastewater is zero because all of the wastewater credit has been applied to irrigation within the same sector. The produced water from oil production cannot meet the demand set by the user control, whereas the produced water from CBM operation can.

This work represents a basic framework to assess the feasibility of water reuse from non-fresh sources. The largest component of the overall water demand is derived from irrigation requirement for feed crops. The water demand for algal operation is less than a quarter of total water demand based on the production unit designed in [19].

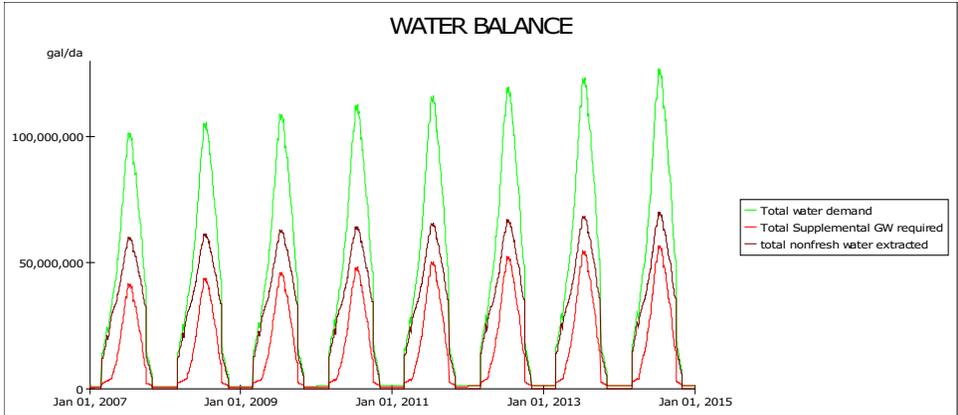


Figure 14a – Overall water demand and supply from fresh and non-fresh sources for Lea County. Total demand (green), supplemental GW required (brown), and total non-fresh water (red).

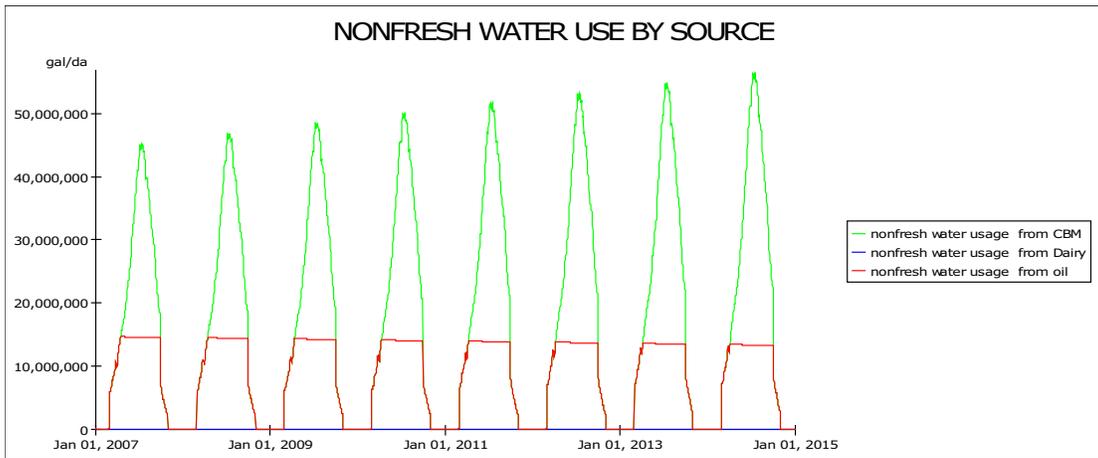


Figure 14b – The relative volumes of non-fresh water for Lea county. Non-fresh water from CBM wells (green), non-fresh water from Dairy (blue), non-fresh water from oil (red).

4. Future Work

This work provides a basic framework for constructing a meaningful analysis coupling biofuel production to various possible water resources. There is still work to be done to reach credible conclusions regarding the feasibility and economic impact of using non-fresh water for algal-based biofuel production. Five categories that need to be added to the current model are listed below. Beyond these additions, attention needs to be given to verification of the model, such that confidence is established that the modeled industries as they operate in New Mexico are being accurately represented.

The amount of electricity required for water transport, pumping, and biomass processing needs to be completed so that the total energy consumption can be estimated for allocating non-fresh water to supplement algal operations.

Conventional natural gas production, which accounts for over 60% of all natural gas production in New Mexico, also produces water that can be beneficially used. The amount of water generated is analogous to water produced in a oil production cycle, but more research needs to be done to create a module for conventional natural gas production.

Competing land use, while stated in the causal loop diagram, is not included in the model. The acquisition of water rights, which is required for expanding dairy and biomass operations, should be included in the model to understand the trade-offs between the cost of acquiring new water versus acquiring non-fresh water. These competing resources and interests are necessary components of New Mexico's water management.

Water quality has been intentionally left out in this work because of the time it would take to integrate a chemical balance into the model. It is not the intent of this research to ignore water chemistry. Because chemical compositions of produced water vary greatly by locations due to the varying geology in the State, it is recommended that a water treatment processes be integrated into the modules.

All of county-specific data, most notably for oil and natural gas production and temperature, need to be completed and integrated into the model. Oil and natural gas data are readily available via the Go-Tech website [26], while temperature data can be obtained through the Natural Climatic Data Center [22].

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Appendix

A. Relative Proportions Slider Construct (RPSC)

David Harris of Sandia National Laboratories developed the Relative Proportions Slider Construct (RPSC). Affectionately known as the “Harris slider”, the construct, which was developed in Powersim Constructor notation, permits the weighted allocation of resources by percentage based upon their starting contributions to the total. The diagram below shows an example of acreage change based on crop feed mix change.

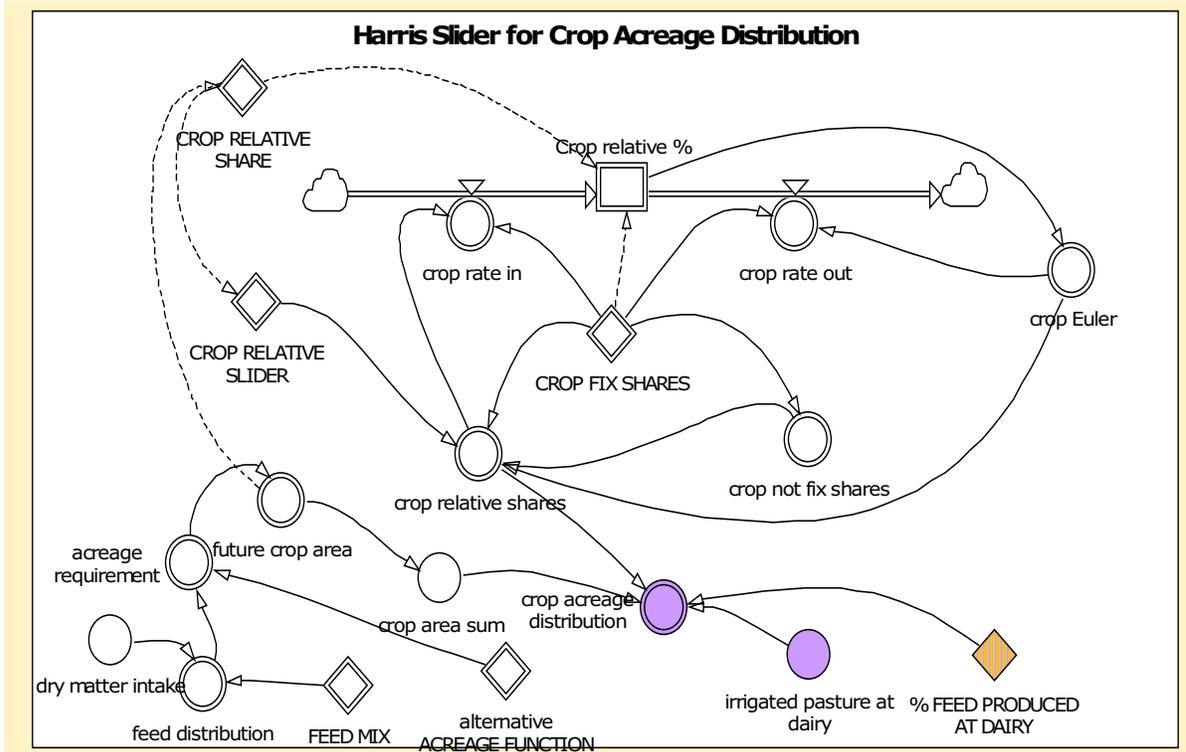


Figure A-1. Stock and flow diagram for the Relative Proportions Slider Construct

The functioning of the RPSC may best be described by an example. Suppose that the percentage contribution by crop type is as shown in the following table. The starting percents, desired contribution and final contributions are shown for an input change that increases the contribution of Wheat to 50% of the total. Each of the other reactor types decreases in proportion to their base case. Table A-1 shows this result.

Reactor Type	Starting percent contribution	Change in contribution	Final contribution
Irrigated Pasture	80%		40%
Alfafa	10%		5%
Corn	10%		5%
Wheat	0%	50%	50%

Changes may be made in succession, each will use the final contribution calculated by earlier changes as the new starting point. For example, in Table A-2 we add a second input change:

Table A-2: Second input change, decrease Irrigated Pasture to 25% after increasing Wheat to 50%			
Reactor Type	Starting percent contribution	Change in Contribution	Final contribution
Irrigated Pasture	40%	25%	25%
Alfafa	5%		6.25%
Corn	5%		6.25%
Wheat	50%		62.5%

The RPSC has another feature that permits fixing the allocation percent contribution of any of the resources. A fixed resource is not included in the redistribution of percentage contributions. This is illustrated in Table A-3 where the Alfafa percent remains fixed. The RPCS is typically used when the simulation is interrupted to induce an input change.

Table A-3: Input change, increase Wheat contribution to 50%, fix Alfafa at 10%				
Reactor Type	Fixed	Starting percent contribution	Change in contribution	Final contribution
Irrigated Pasture	N	80%		35.56%
Alfafa	Y	10%		10%
Corn	N	10%		4.44%
Wheat	N	0%	50%	50%

Distribution:

1	MS1413	Grant Heffelfinger	8330	
1	MS1413	Kathe Andrews	8333	
1	MS0895	Tony Martino	8332	
1	MS9292	Todd Lane	8321	
1	MS9406	Ben Wu	8125	
1	MS9291	Blake Simmons	8755	
1	MS9409	Chris Moen	8757	
1	MS1110	Vipin Gupta	6337	
1	MS1137	Aldo Zagonal	6321	
1	MS1138	Steve Conrad	6322	
1	MS1108	Mike Hightower	6332	
1	MS0719	Phil Pohl	6766	
1	MS0735	John Merson	6310	
1	MS0735	Ray Finley	6313	
1	MS1350	Vince Tidwell	6313	
1	MS1350	Howard Passell	6313	
1	MS1350	Len Malczynski	6313	
1	MS0735	Ron Pate	6313	
1	MS0754	Rich Kottenstette	6316	
1	MS0754	Tom Mayer	6316	
1	MS0754	Mark Rigali	6316	
1	MS0706	Peter Kobos	6312	
1	MS0706	Tom Drennen	6312	
1	MS0706	Allen Sattler	6312	
1	MS9018	Central Technical Files	8944	(electronic)
1	MS0899	Technical Library	9536	(electronic)
1	MS0123	D. Chavez, LDRD Office	1011	
1	MS0115	CRADA Administration	1323	
1	MS0161	Patent and Licensing Office	11500	
1		Victor Cabrera Extension Dairy Specialist New Mexico State University		