University of Nevada, Reno

Modeling Halophytic Plants to Improve Agricultural Production and Water Quality in Arid and Semi-Arid Regions

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Hydrogeology

by

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May, 2014

THE GRADUATE SCHOOL

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prepared under our supervision by

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Entitled

Modeling Halophytic Plants To Improve Agricultural Production And Water Quality In Arid And Semi-Arid Regions

be accepted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

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Abstract

A major problem for irrigated agricultural production in arid and semi-arid environments is salinization of land. Irrigated land accounts for about one third of the world's food, but nearly one fifth of irrigated lands are salt affected and suffer from reduced yield due to soil salinization. Many farmers worldwide currently leach their lands to remove salt, but this practice can create further problems such as polluting nearby water sources with salt, fertilizer, and pesticides. Most common cultivated crops are known as glycophytes and suffer from reduced yield when subjected to salt stress. However, about 1% of the world's flora are known as halophytes, or plants that are capable of completing their life-cycle in higher saline soil or water environments. Halophytes are not commonly cultivated, but may be useful for human consumption, biofuel, or animal consumption. As a first step to assessing the potential of halophytic plants for salinity management, the Agricultural Policy/Environmental Extender (APEX) model was updated with a module to simulate plant-water-soil salinity dynamics using electrical conductance. The halophytes *Atriplex nitens*, *Climacoptera lanata*, and *Salicornia europeae* were parameterized in the APEX model's plant database. Plant, soil, and water data from field sites in the Central Kyzylkum and Khorezm regions of Uzbekistan were used to set up APEX models for two field sites. Measured data collected from the two field sites in 2013 were used to assess model performance. Although APEX ran with the salinity module and produced output, analysis of the output indicated that further work is needed to produce a model that will be useful for assessing salinity management with halophytes. A sensitivity analysis was performed on 47 parameters in APEX, and 14 were found to be sensitive for biomass, crop height, and soil electrical conductance (EC) output, including soil parameters such as soil albedo, sand content, and silt content. After running 500 simulations with random combinations of sensitive parameters, best fit results between observed and modeled values for crop biomass, crop height, and soil EC had deviations of as much as 42.5 tonnes/ha biomass, 200 cm of crop height and 23 mS/cm of EC, respectively. Suggestions for model improvements include enabling the modeling of individual salt ions because plants may experience toxic effects of different ions. Additionally, halophytes and conventional crops will die or fail to germinate under threshold salinity levels, but this relationship was not demonstrated with the model. Some halophytes have an increased yield under moderate soil salt levels, and salt can percolate into deeper soil layers, but these phenomena were also not simulated by the model. Future iterations of this project will benefit from more field data. Daily weather from the modeled time period should be used instead of generated weather based on monthly statistics. Plant and soil data should be taken at more frequent intervals, preferably at least once a month.

Acknowledgments

My education and research was made possible through the generous funding from the Nevada Agricultural Experimental Station via the Hatch Grant. I also received assistance from the Joan Comanor Scholarship and the Clare Mahannah Memorial Scholarship.

Prior and concurrent projects also enabled this research. The Partnership for Enhanced Engagement in Reseach (PEER) grant entitled “Utilization of low quality water for halophytic forage and renewable energy production” provided field data for which to parameterize and test the salinity module. The PEER project was funded in part because of a prior project: NSF Grant 0838239 entitled “Investigating pesticide contamination in small lakes in Khorezm, Uzbekistan.”

Dr. Jaehak Jeong with the Agricultural Research Station (ARS) in Temple, TX wrote the code for the salinity module with help from Dr. Cole Rossi with the Bureau of Land Management (BLM) in Salt Lake City, UT. I received help from Dr. Jim Kiniry (ARS, Temple, TX) with parameterizing the 3 halophytic plants into the APEX model. Additionally, Jay Davison with the University of Nevada Cooperative Extension in Reno, NV provided us with information about agriculture and halophytic plants in the Great Basin. Dr. Laosheng Wu helped theorize a simple modeling mechanism that would enable halophytes to suffer reduced yield under certain salinities.

Dr. Natalya Akinshina with the International Center for Biosaline Agriculture in Tashkent, Uzbekistan helped by providing data from the PEER project field sites. Izzat Kuryazov and Murod Sultanov, both with Khorezm Rural Advisory Support Service (KRASS) in Urgench, Uzbekistan also helped provide information about the field site located in the Khorezm region.

Joel Hupp and Helaine Berris, both undergraduates at the University of Nevada, Reno, helped me with running the model and assessing the performance. Joe Sapin, a graduate student at the University of Nevada, Reno, helped me analyze weather data from Uzbekistan.

I would like to acknowledge and thank my committee members, Dr. Bob Nowak, Dr. Michael Rosen, and Dr. Kristina Toderich with all of their help and advice throughout the duration of this project. Finally, I would like to thank my adviser, Laurel Saito. Her help, guidance, and support, and attention to detail were invaluable to me during the project. I am extremely appreciative for her helping me grow as a scientist and engineer.

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1. Introduction

1.1 Project Background

One of the major challenges for irrigated agricultural production is salinization of land, particularly in arid and semi-arid regions. Soil salinization can occur naturally or anthropogenically. Human-induced soil salinity is called secondary salinization and can be caused by agricultural lands being irrigated with saline water or by poor drainage practices (Munns 2005). In arid and semi-arid regions, not enough rain falls to naturally flush salt that comes into soil through irrigation water, so the salts are left to accumulate (Vahidreza and Mehdi 2010). Water that does not contain high concentrations of salt can also contribute to soil salinization if it is allowed to evaporate because it concentrates salts that were left behind (de Oliveira et al. 2013; Figure 1). Most conventional crops are known as glycophytes, or plants that are sensitive to salt stress because they lack the genetic basis for salt tolerance (Glenn et al. 1999). Accumulating salts cause reduced crop yields, and in some cases, a complete loss of production (Yamaguchi and Blumwald 2005). Worldwide, nearly 20% of irrigated lands are negatively impacted by salts (Munns 2005).

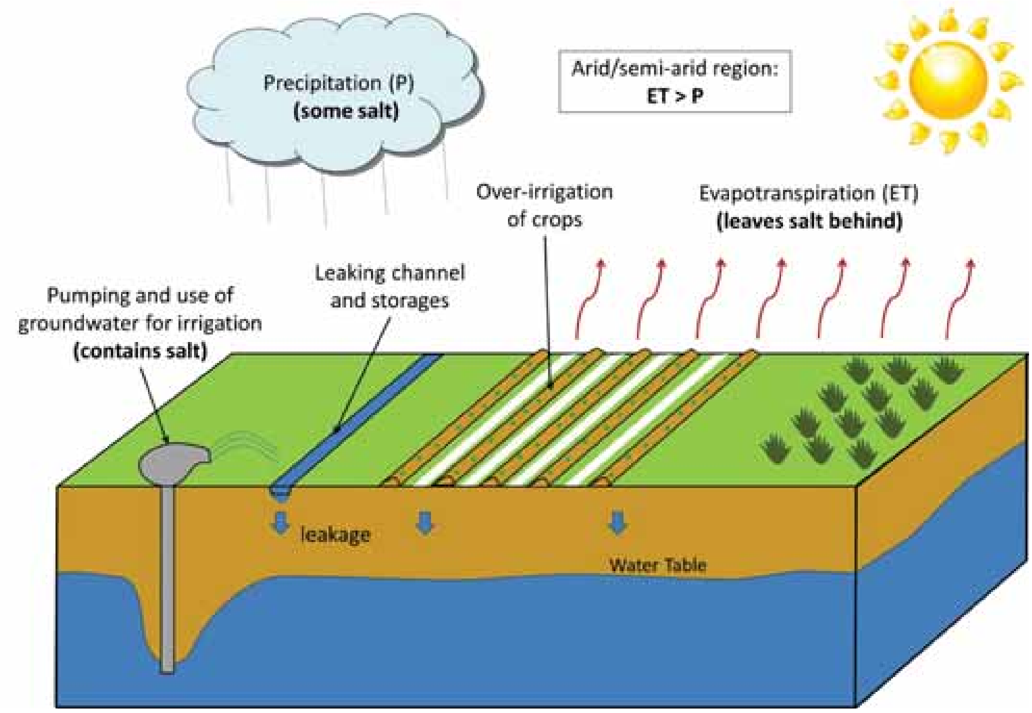


Figure 1: Schematic of the causes of human-induced soil salinization. Adapted from de Oliveira et al. (2013).

Reduced agricultural productivity is only one way that accumulating salts negatively impact the environment. Salts can also pollute nearby freshwater sources. In some areas of the world, farmers seasonally leach their land to remove salts before planting crops. Leaching is only a temporary solution, however, and salts, fertilizer, and pesticides flushed from agricultural lands may eventually end up polluting nearby water bodies such as lakes and groundwater (Oberkircher et al. 2011).

The Great Basin in the western United States is a multi-state endorheic basin in the western United States. As with much of the western United States, this region has soil salinity values greater than 4.0 dS/m (Figure 2;Tanji and Wallender 2012; Anning et al. 2007). The basin is arid and semi-arid, with annual precipitation ranging from 10 to 20 cm with little summer or spring rain (Harris et al. 2001). In Nevada, the majority of cultivated land is affected to varying degrees by soil salinization. Soluble salt is managed by applying a leaching fraction during irrigation; often subsurface drains are used to move saline water away from fields. In areas with sodium salts, sulfur or gypsum is often added prior to leaching (J. Davison, personal communication August 2013).

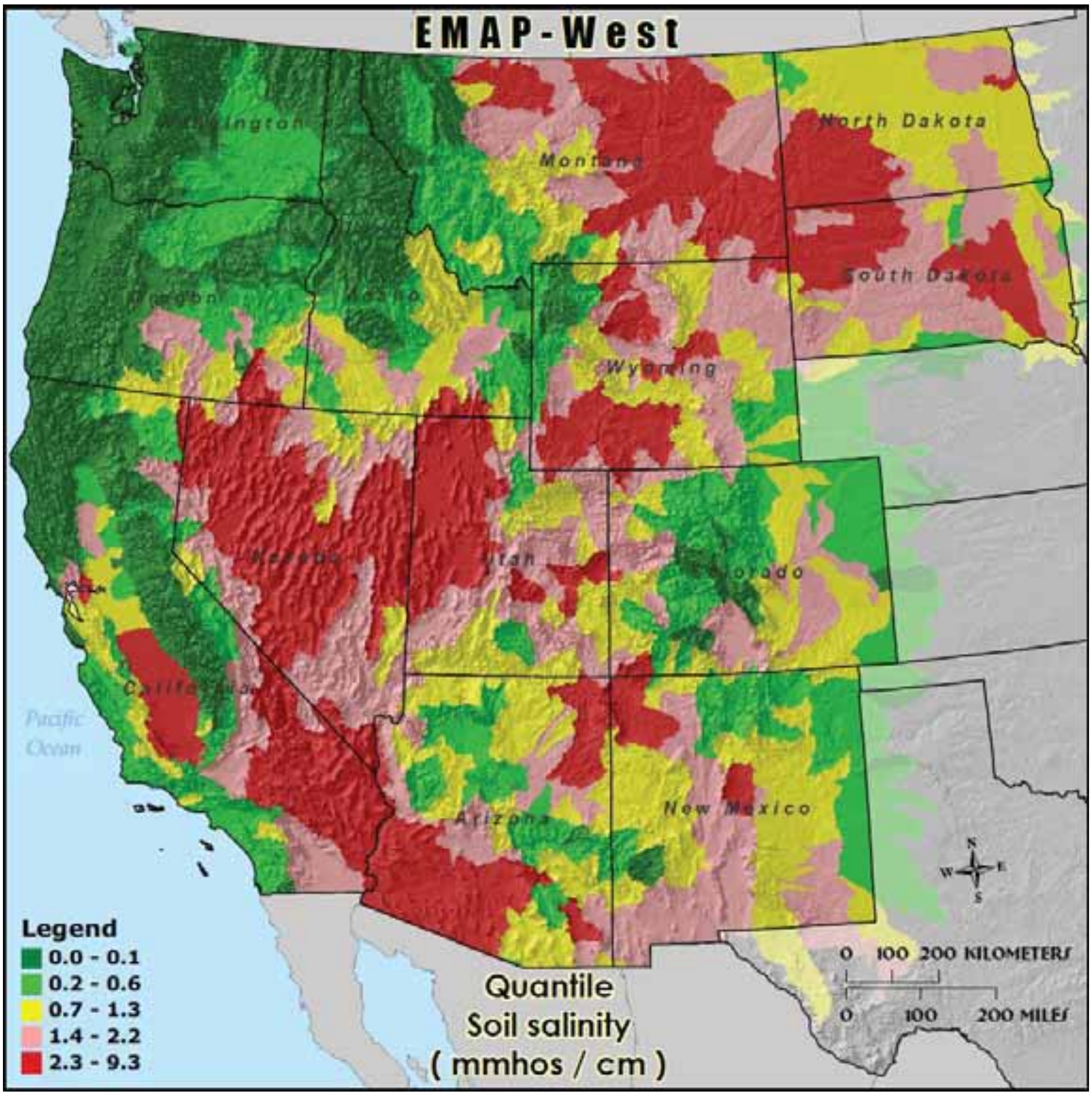


Figure 2: Soil salinity in the western United States (U.S. Environmental Protection Agency 2011)

Uzbekistan, in Central Asia (Figure 3), is also suffering from soil salinization (Micklin 2007). Uzbekistan is located in a mostly arid region in the Aral Sea Basin (Rakmatullaev et al. 2012; Micklin 2007). Mean annual precipitation (100-300 mm) is exceeded by evaporation (1,600-2,200 mm) in Uzbekistan, which also experiences hot summers and cold winters (Rakmatullaev et al. 2012). Several regions in the Aral Sea Basin are experiencing decreased agricultural production and increased freshwater pollution caused by salinization (Micklin 2007). Until 1960, the Aral Sea was the fourth largest lake in the world, but its area and volume have since decreased by 74% and 90%, respectively. The Aral Sea's decrease in size is due in large part to a change in land use in the Aral Sea Basin in which the major rivers that flow into the Aral Sea were diverted to provide irrigation water to an additional 2.9 million hectares of agricultural land (Micklin 2007). Thus, much of the water that would otherwise be flowing into the Aral Sea is now being lost through evapotranspiration, infiltration to groundwater, or used for irrigation. The land use change in the 1960s was done in an effort to make the area a cotton monoculture to supply textile manufacturers in the former Soviet Union (Oberkircher et al. 2011). The change in land use has resulted in increased soil salinity that has reduced yields of conventional crops. It has also resulted in a higher water table and pollution of nearby lakes with salts, fertilizers, pesticides, herbicides, and cotton defoliants (Micklin 2007; Shanafield et al. 2010; Ibrakhimov et al. 2011; Ibrakhimov 2007).

Salinity issues in arid and semi-arid regions are similar. Salinity management techniques that work in Uzbekistan may work in climatically comparable areas such as the Great Basin.

Figure 3: Location of the Khorezm and Central Kyzylkum regions of Uzbekistan. (Wikipedia 2014; Central Intelligence Agency 2014).

One potential way of mitigating the problems of agricultural production loss and fresh water pollution is to plant and harvest crops capable of tolerating high salt concentrations. Most cultivated crops are glycophytes that can be negatively affected by salt in several ways. First, the osmotic effect negatively affects the plant because high salt concentrations outside of the plant reduce soil water osmotic potential. Osmosis is a process in which water naturally moves across a semi-permeable membrane from areas with less solute to areas with more in order to reach equilibrium (Brown et al. 2000). Plants that cannot survive with high salt content must exert energy to reverse the osmosis process and draw water into their cells. This energy would otherwise go toward other vital processes such as plant growth, and it can also injure cells in transpiring leaves (Munns 2005). Ultimately, the osmotic effect can result in decreased yields. Another effect of soil salinization is the toxicity effect because some plants find certain ions to be toxic (Munns 2005). And thirdly, nutrient imbalances negatively affect plants because high ratios of certain ions (such as Na^+ and Cl^-) to others may reduce the ability of these plants to access these other ions (Wu 2002).

Some plants, however, are capable of completing their life cycle in highly saline conditions. These salt-tolerant plants are known as halophytes. Salt tolerance has two important aspects—the degree of salt-stress that can be tolerated by an individual plant, and the ability of that plant to successfully reproduce under saline conditions (Breckle and Wucherer 2012). Halophytes deal with salts through a variety of control mechanisms (Breckle and Wucherer 2012; Table 1). Overall, plants manage leaf salts by ion exclusion, ion excretion by salt glands and bladders, or succulence (Atwell et al. 1999).

Ion exclusion involves the plant roots regulating their salt load to their sensitive organs. Ion exclusion is generally done at the root zone or by internal exclusion mechanisms (Grasso and Bickel 1999). Ion exclusion at the root level is not an efficient mechanism because of the powerful effects of osmosis. Internally, plants can exclude salts from sensitive organs by sequestering salt ions in specialized tissues and removing them from the transport system. Rapid leaf turnover is a method of internal salt exclusion in which old leaves with a high salt content are regularly replaced by younger leaves (Breckle and Wucherer 2012). Ion exclusion is especially important for perennial halophytes because they live longer and need to regulate salt intake longer than annual plants.

Ion excretion happens when plants have salt glands or salt bladders that are capable of shifting ions from mesophyll tissues to leaf surfaces where they eventually wash off with rain or blow off with wind. Salt glands are organs that consist of specialized cells that excrete salt ions (Atwell et al. 1999). Excretion takes energy, and therefore generally occurs at greater rates in the daytime. Salt bladders are modified epidermal hair cells that accrue salt ions and occasionally rupture, releasing their contents. Salt bladders consist of two cells: a stalk cell that transports salt ions from mesophyll cells to bladder cells, and a bladder cell that expands as it accumulates salts (Atwell et al. 1999).

Table 1: Salt control mechanisms of halophytes (modified from Breckle and Wucherer 2012). EX: exocrinohalophytes, LSu: leaf-succulent euhalophytes, NoH: nonhalophytes, NX: endocrinohalophytes, Ps: pseudohalophytes, SSu: stem-succulent euhalophytes, Su: xerohalophytes

Mechanism	**Halophyte type**
Avoidance	
Growth only during favorable seasons	NoH, Ps, Su
Limitation of root growth and absorption activity to distinct soil horizons	Ps, NoH
Evasion and adaption processes	
Selectivity against Na^+ and Cl^-	NoH, Ps, Su
Leaching of salt from shoots	NoH, Ps
Diversion of salt out of assimulating tissues	Ps
Compartmentation of salt within plant, within tissues, within cells	All plants
Accumulation of salt in xylem panenchyma in roots and shoots	All halophytes
Synthesis of organic solutes	All plants, Su
Retranslocation of salt to roots and recretion by roots	Halophytes
Disposal of older plant parts ("salt-filled organs")	Ps, all halophytes
Recretion by gland-like structures on shoots	
By salt glands	EX
By salt bladders	NX
Tolerance	
Increasing salt tolerance of tissues, cells, organelles	LSu, SSu, NX, EX, Ps
Increase in halosucculence	
Increasing leaf-succulence	LSu, Ps
Increasing stem succulence, reduction of leaves	SSu

Succulent plants often have thick or fleshy leaves that contain large and highly vacuolated cells. These cells are capable of handling large water content (as mass) per unit of leaf area (Atwell et al. 1999, Khamraeva 2012). The large vacuolated cells can store more salt per unit of transpiring surface area because leaf thickness can continue to increase after reaching maximum leaf surface area, resulting in more storage for incoming salts. The additional salt storage space eases the strain that salts can have on cytoplasmic compartments (Atwell et al. 1999). Succulence has two components: a genetically controlled succulence and a modifying variable that can be induced by salts. Succulent plants can be stem or leaf succulent. Leaf succulent halophytes often have fleshy leaves, whereas stem succulent halophytes are often leafless (Breckle and Wucherer 2012). Succulents accumulate more Na^+ and Cl^- (3000-5000 mmol/kg) than other species (Breckle and Wucherer 2012).

Breckle and Wucherer (2012) compiled a table of how halophytes deal with salts in the different categories of avoidance, evasion and adaptation processes, and tolerance (Table 1). Exocrinohalophytes excrete salts externally with salt glands, and endocrinohalophytes separate salts but keep them within the plant with organs known as salt bladders. Leaf-succulent halophytes have large vacuolated cells in the leaves and stem-succulent halophytes have vacuolated cells in the stem that correspond to where the majority of internal salt is located. Xerohalophytes are defined as growing in dry climates where soil is salty and dries out seasonally. Pseudohalophytes are crops that avoid salt. Overlap between all halophyte groups occurs.

In Uzbekistan, halophytes have already been replacing native vegetation (Micklin 2007). Domestication of these salt-loving plants could potentially reduce or maintain soil salinity in irrigated lands. Unlike glycophytes, halophytes are able to grow in saline conditions and contain higher salt concentrations. Harvesting halophytic plants could remove salt that was stored in or on the plants out of the soil system, thereby improving agricultural production and environmental quality. A reduction in soil salts may also reduce the amount of salts that flow into nearby freshwater sources. Halophytes could also potentially be utilized for human consumption, livestock fodder, biofuel, or other purposes (Breckle and Wucherer 2012).

Thus, it is hypothesized that halophytes can be used to decrease soil salinization on lands affected by soil salinization and can restore saline agricultural land for conventional crop production. Ideally, farmers would eventually be able to grow conventional crops given enough time after planting and harvesting halophytes. It is also hypothesized that halophyte cultivation will decrease the amount of salt pollution in nearby water bodies. To fully investigate these hypotheses, field and laboratory experiments and computer modeling are necessary. This thesis addresses only the modeling aspect by developing and evaluating a computer model that can be used to address these hypotheses. Eventually, an economic analysis of model results will also be useful, but that is beyond the scope of the current project.

The objective of this project is to develop and evaluate a model that can simulate halophyte planting, growth rate, and harvest under differing management strategies. The model will also track salinity in plants, soil, and water. If model development is successful, the following questions will be addressed:

Question 1: Can planted and harvested halophytes remove or maintain soil salts?

Question 2: What management strategies (e.g., fertilizer, irrigation, etc.) are most effective for removing soil salts?

1.2 Related Ongoing Projects

1.2.1 PEER Project

Dr. Kristina Toderich, regional representative of the International Center for Biosaline Agriculture in the Tashkent, Uzbekistan sub-office, obtained a Partnerships for Enhanced Engagement in Research (PEER) project funded through the National Science Foundation (NSF) and the United States Agency for International Development (USAID) in 2011. The main objective of her project entitled “Utilization of low-quality water for halophytic forage and renewable energy production” is to test some fodder halophytes in saline environments by using slightly saline water for irrigation in two representative field sites in the Central Kyzylkum and Khorezm regions in Uzbekistan.

At both sites, 8 halophytes are being cultivated. Four species of halophytes, *Atriplex nitens, Climacoptera lanata, Salsola slerantha,* and *Kochia scoparia*, were planted in pure stands on February 4, 2014. These 4 halophytes were also intercropped with salt-tolerant crops including sorghum, millet, artichoke, and licorice. Alfalfa (*Medicago sativa*) was grown as a control crop. Plant survival rates, growth according to different phenological stages, and green biomass and seed yield related to soil salinity are being measured.

The Shurkul Koshkopir site in Khorezm was chosen because of a previous NSF project that looked at saline lakes in the area, including Shurkul Koshkopir lake which is located adjacent to the field site. The soil has a high clay content, and the salinity of the soil in the area is human-induced and chloride-rich. An observation well was installed for irrigation and groundwater monitoring.

The Kyzylkezek site in the Central Kyzylkum desert has a sandier soil than the site near Shurkul Koshkopir. This site was chosen because of previous projects in the area by Dr. Toderich. It has natural rather than human-induced salinity, and the salinity is sulfate rich. The site has a number of warm artesian wells that average about 38-40 degrees Celsius.

Both the Khorezm and Kyzylkezek field sites have similar elevations at 90 m and 130 m respectively, but the climate is different. The average monthly maximum temperatures are very similar, but Kyzylkezek has cooler temperatures in the winter (Figure 4).

Khorezm is also less windy and less wet in the summer than Kyzylkezek (Figure 5A, 5C). In wintertime, the Kyzylkezek site is wetter than Khorezm. Both sites have similar relative humidity except in summer months, when Khorezm is more humid (Figure 5B).

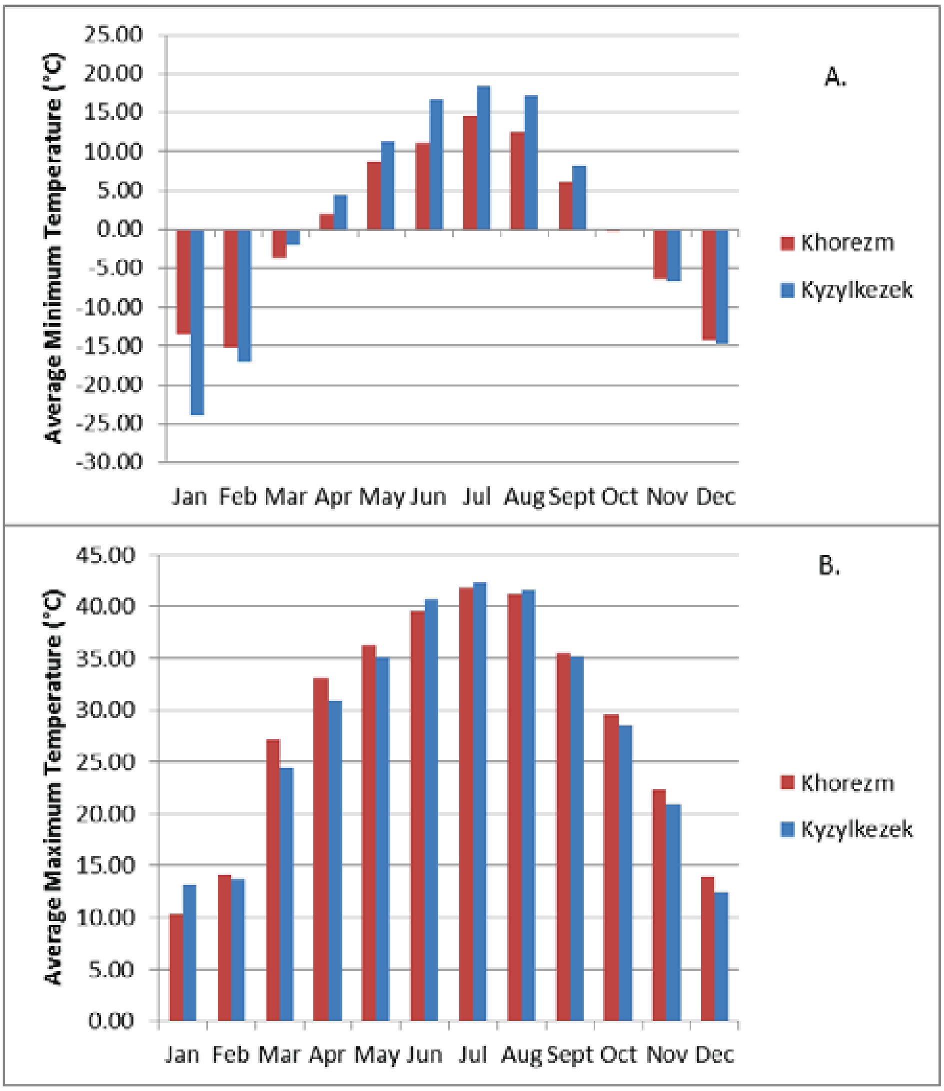


Figure 4: Average monthly A) minimum temperature, and B) maximum temperature for Khorezm and Kyzylkezek for 2006 to 2013.

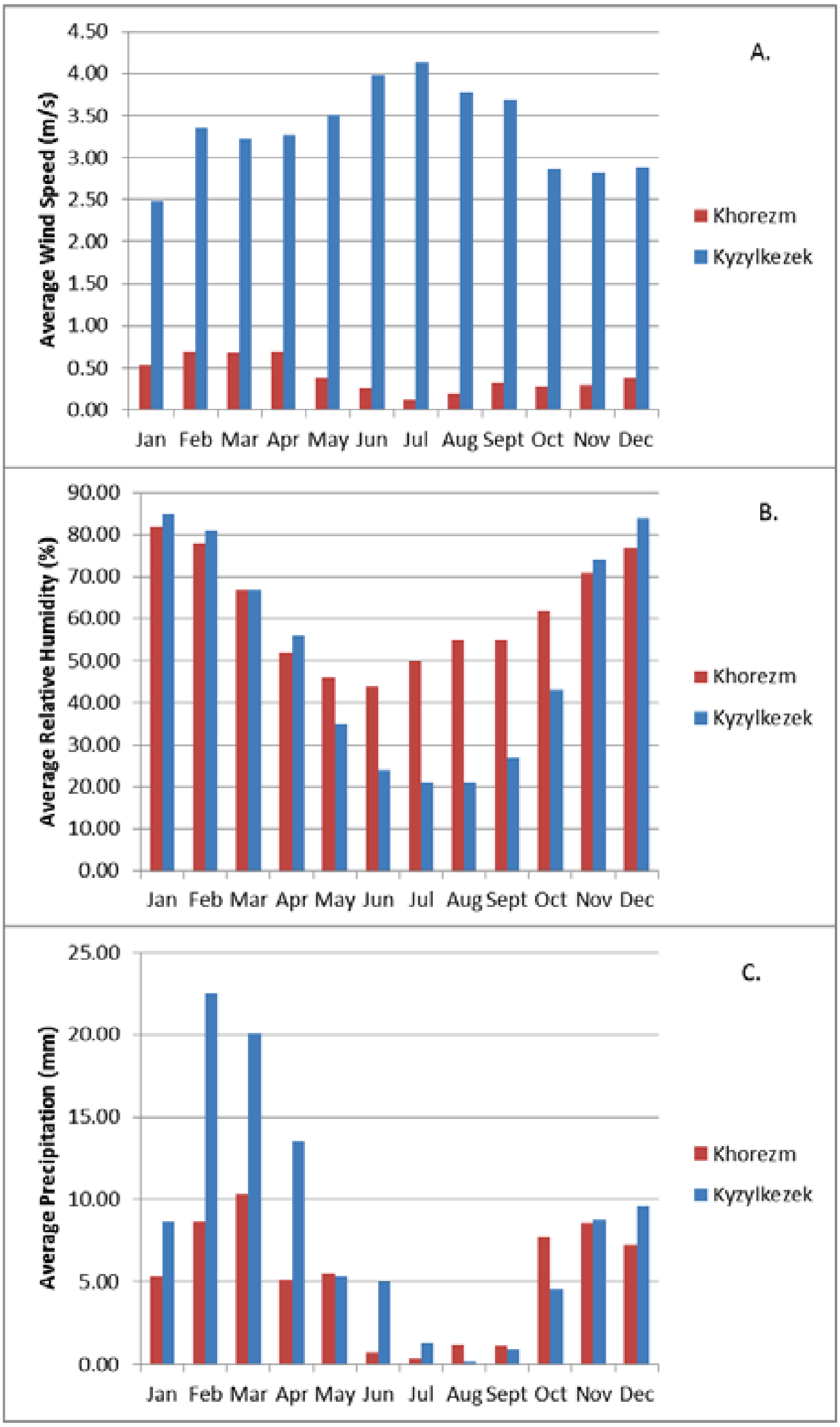


Figure 5: Average monthly A) wind speed B) relative humidity, and C) precipitation for Khorezm and Kyzylkezek for 2006 to 2013.

Soil samples from the two sites were collected in August 2012, November 2012, March 2013, and August 2013 from the 0-20 cm horizon, and occasionally at the 20-40 cm, 40-60 cm, and 60-80 cm horizons. Soil samples were tested for pH, electrical conductivity (EC), alkalinity (A_T), chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), total dissolved solids (TDS), the nutrients potassium (K^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}), humus, and soil organic carbon. Proportionately, the Kyzylkezek field site is dominated by $Ca^{2+}$and SO_4^{2-}, whereas the Khorezm site primarily contains Na^+ and Cl^- (Figure 6). Figures 7 and 8 show average EC and TDS, and Figure 9 shows average HCO_3^-, Cl^-, SO_4^{2}, Ca^{2+}, Mg^{2+} and Na^+ in soils for both Khorezm and Kyzylkezek sites in November 2012. Salinity was much higher at Khorezm as compared to Kyzylkezek (Figure 7). However, in the 60-80 cm layer, EC, SO_4^{2-}, Ca^{2+}, and TDS were greater for Kyzylkesek (Figures 7 and 8). The Kyzylkezek site also has a greater HCO_3^- concentration.

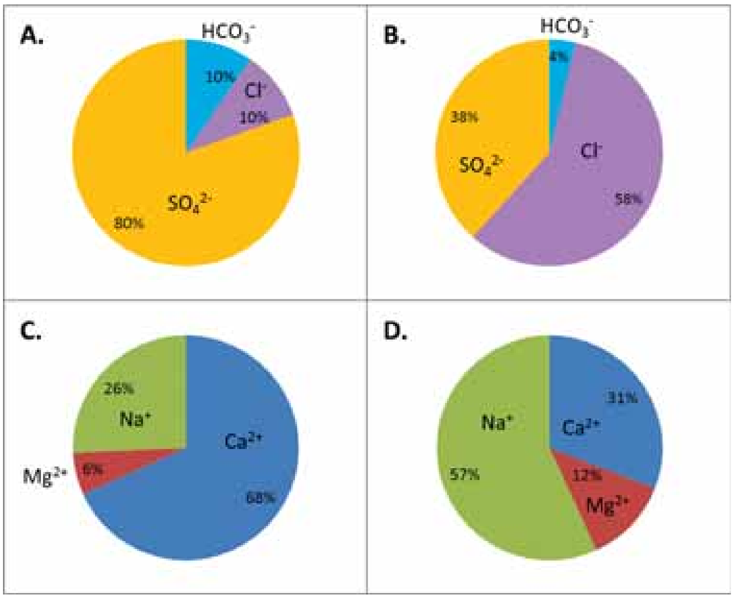


Figure 6: A) Anions (HCO_3^-, Cl^-, SO_4^{2-}) in Kyzylkezek soils; B) anions in Khorezm soils; C) cations (Ca^{2+}, Mg^{2+}, Na^+) in Kyzylkezek soils; and D) cations in Khorezm soils in August 2012.

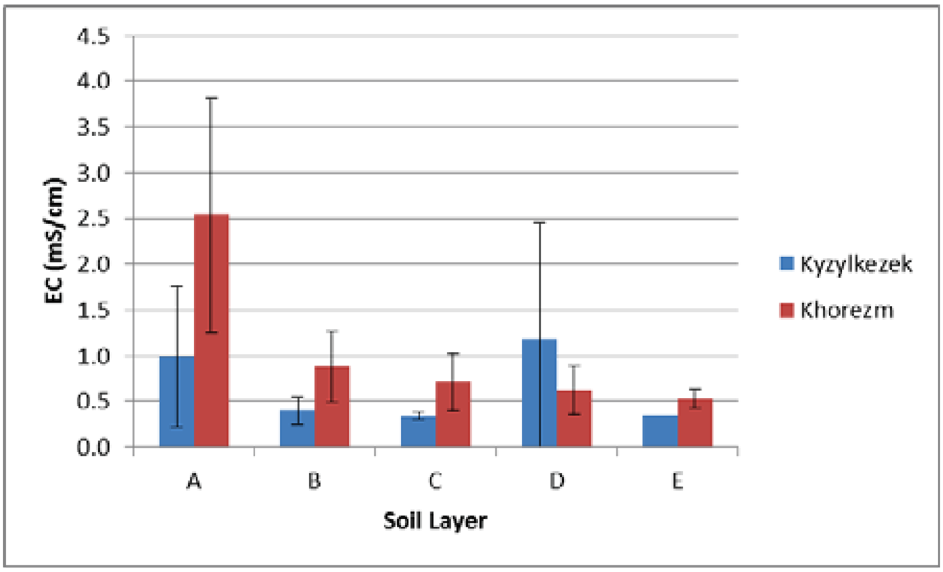


Figure 7: Average EC in soil layers in Kyzylkezek and Khorezm agricultural plots and standard deviations for all measured dates.

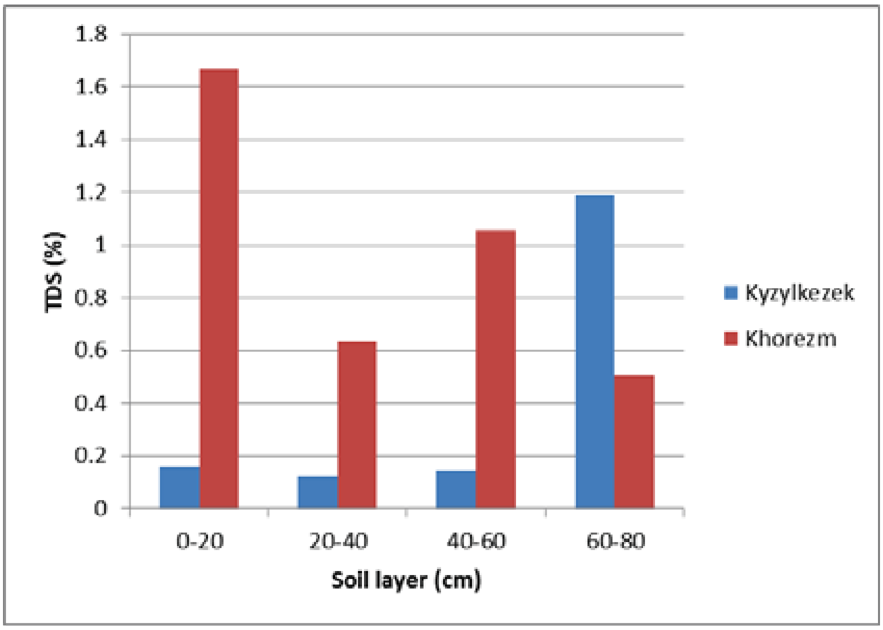


Figure 8: Average total dissolved solids (TDS) in soil layers in Kyzylkezek and Khorezm agricultural plots in November 2012.

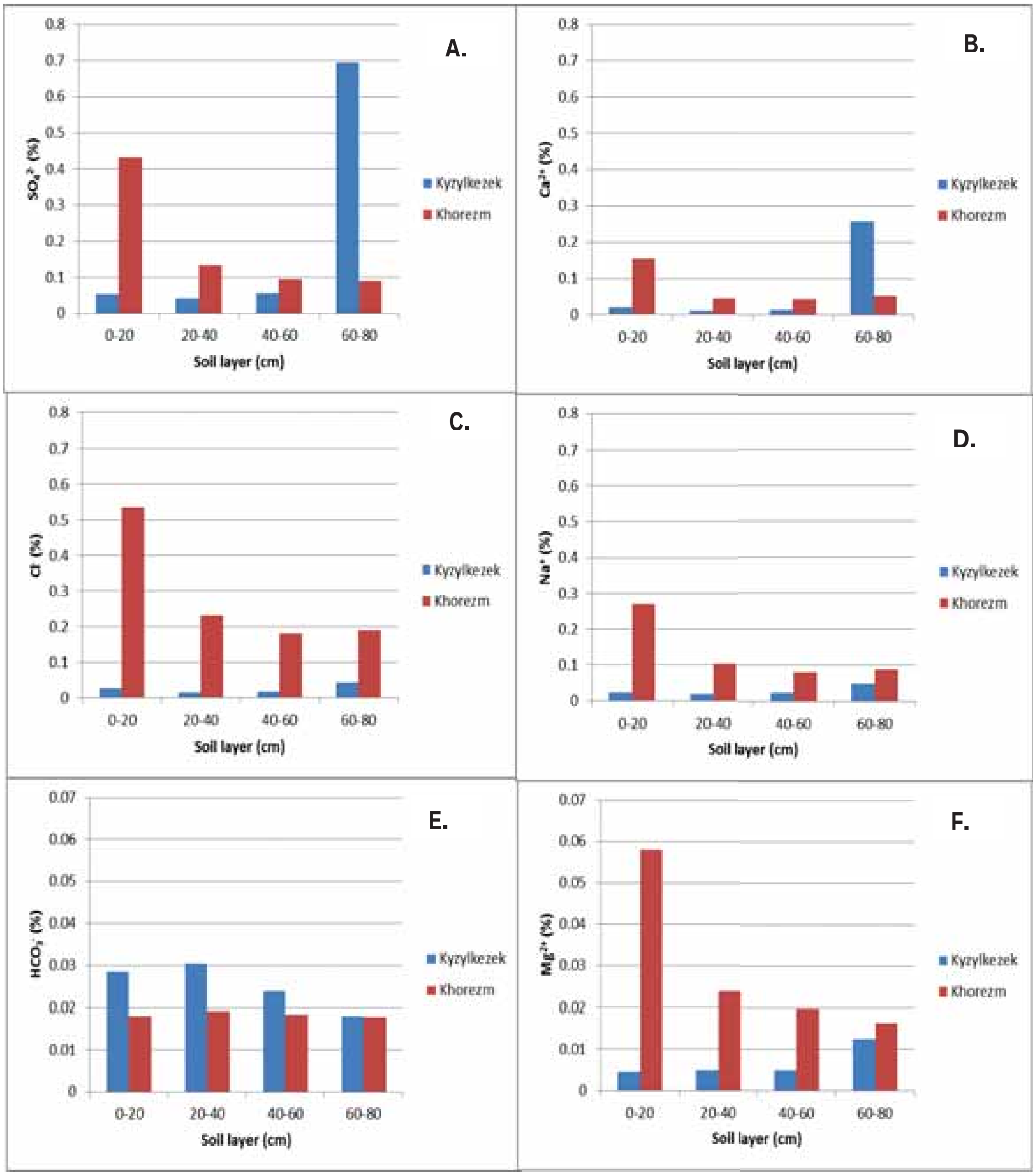


Figure 9: Average A) SO_4^{2-} B) Ca^{2+} C) Cl^- D) Na_+ E) HCO_3^- F) Mg^{2+} concentrations in soil layers in Khorezm and Kyzylkezek in November 2012. Note that the scale is different for HCO_3^- and Mg^{2+}.

Water samples were also taken from Shurkul Koshkopir Lake, the irrigation channel, and ground water in Khorezm, and from the artesian wells, drainage canal, and reservoir near the site in Kyzylkezek. Samples were analyzed for pH, hardness, ammonia (NH_4^+), nitrite (NO_2^-), nitrate, phosphate, total phosphorus (P), hydrocarbons, Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+}. Stiff diagrams for Shurkul Koshkopir lake water in Khorezm and artesian well water in Kyzylkezek show that though the magnitude of ion concentrations are different, general ionic compositions are similar (Figure 10).

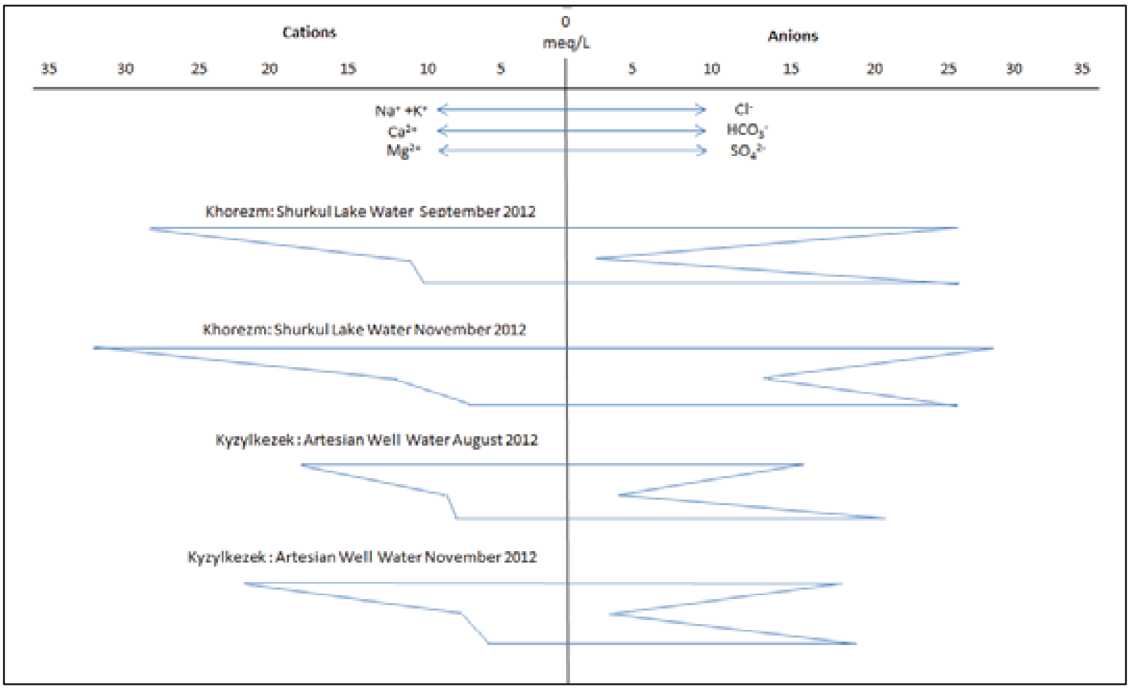


Figure 10: Stiff diagram for Shurkul Koshkopir lake water in Khorezm and artesian well water in Kyzylkezek in 2012.

Groundwater at Shurkul Koshkopir is saline with EC greater than 10 mS/cm. Shurkul Koshkopir lake was determined to be a better irrigation source because it is less saline, with EC of 4 to 6 mS/cm. Soil salinity in this area is also high (Figure 11). None of the cultivated plants grew at this site in 2013, although *Karelinia caspia* grew wild at the site (Figure 12). Wild species of *Tamarix laxa*, *T. rammossima*, *Glychyrryza glabra*, *Aelaeropus litoralis*, single draft individuals of *Phragmites communis*, and annual species of *Salsola* were found growing near the field site during the summer of 2013.

The reason for the extremely low growth of cultivated crops in Khorezm could be caused by a number of variables including:

- The high chloride salinity may be more detrimental to plant growth than other concentrations and types of salinity (Lauchli and Grattan 2012).
- Just after planting, highly saline groundwater (56.4 mS/cm) was used to irrigate the site (Izzat Kuryazov Personal Communication 2014). This highly saline water may have negatively impacted seed germination and seedlings survival. Only lake water has been used to irrigate crops since then.
- A winter storm with freezing conditions occurred just before planting in February 2013. Replanting did not occur again until mid-April which was perhaps too late to plant the crops.

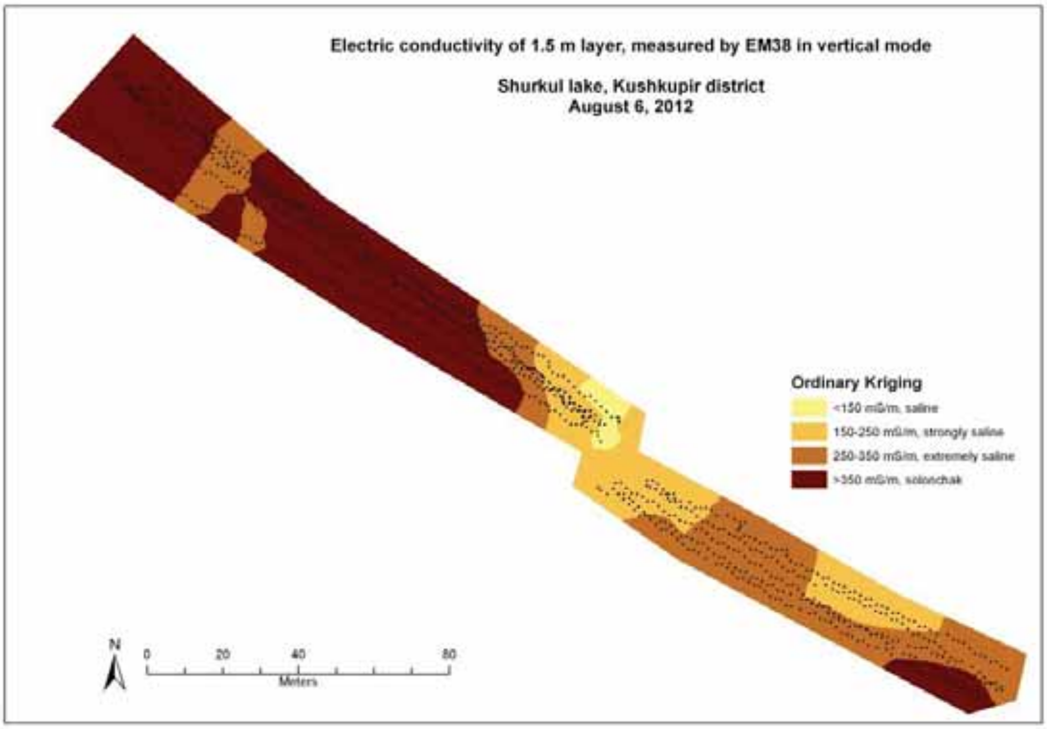


Figure 11: Interpolated map of salinity near Shurkul Koshkopir lake in the Khorezm region in Uzbekistan. (Toderich 2013a).

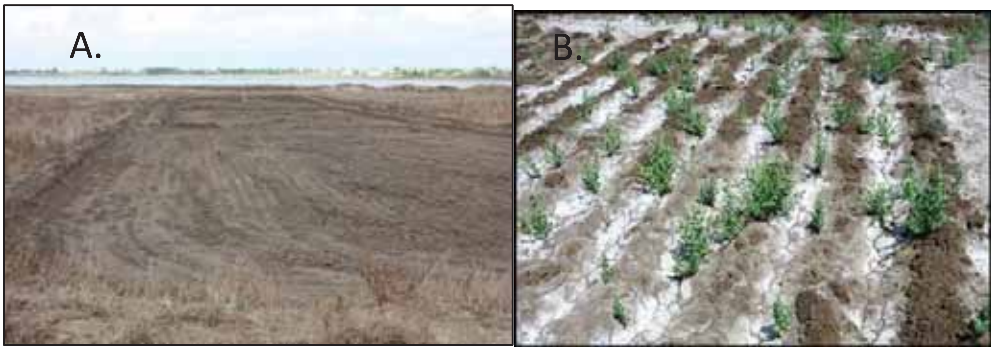


Figure 12: Khorezm field site in A) April 2013 with nothing growing and B) August 2013 with wild *Karolinia caspia*

At the Kyzylkezek field site, annual halophytes *Kochia scoparia*, *A. nitens*, *C. lanata*, *S. arcuata*, and several perennial halophytes including *G. glabra* successfully germinated, grew, and were harvested (Figure 13). The date of seed bedding, number of plants per hectare, yield of fodder mass, yield of seeds, and the period of vegetation were all recorded.

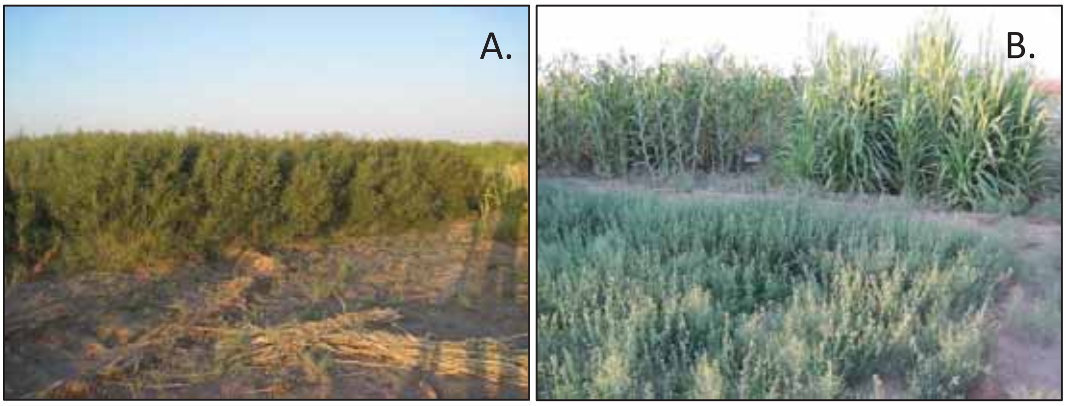


Figure 13: A) *Glycyrrhiza glabra* **and B)** *Salicornia arcuata* **and** *Climacoptera lanata* **at Kyzylkezek site in August 2013.**

1.2.2 Greenhouse Experiments

At the University of Nevada, Reno, Dr. Bob Nowak and Wailea Johnson are doing a greenhouse study on the halophytes *Atriplex hortensis* (also known as *A. nitens*) and *Salicornia bigelovii*. The study included three experiments. The first experiment, which has been completed, was a germination trial at four water salinity levels (1, 3, 6, 12 dS/m) with 5 replicates with 25 seeds for each salinity level. The experiment showed that *A. nitens* can germinate well with water up to 3 mS/cm, but rarely can germinate at greater water salinity levels. *S. bigelovii* did not germinate at any of the salinity levels. The second experiment, which is nearly complete, examined the effect of water salinity on growth of *A. nitens* (Table 2). Preliminary results show that *A. nitens* generally does not grow well at salinities greater than 5 mS/cm. One pot of *A. nitens* was unable to survive at irrigation water salinity of 3 mS/cm. A third experiment to be conducted will test the combined effects of water and soil salinity on *A. nitens* growth.

Table 2: Data from the second greenhouse test for *Atriplex nitens*. Cot stands for cotyledon, which is a seed leaf.

		9/24/2013		10/14/2013		10/24/2013	
Pot #	Treatment (mS/cm)	# leaves (+cot)	Height (cm)	# leaves (+cot)	Height (cm)	# leaves (+cot)	Height (cm)
1	1	10	3.9	18	15.6	18	36.8
2	4	9	4	15	9.4	12	21.4
3	1	10	2.9	12	9.8	14	14.2
4	5	10	5.2	12	11.8	12	19.1
5	5	10	4.3	Died	-	Died	-
6	3	8	2.8	8	5.2	10	11
7	4	10	2.5	12	8	12	16.6
8	3	10	2.9	12	9.5	12	19.3
9	1	10	3.1	12	10	14	23.2
10	4	10	5.2	16	12.5	14	26.1
11	1	6	2.4	10	5.5	8	8.7
12	5	10	3.5	10	8.9	12	19.3
13	5	10	2.4	10	6.8	Died	-
14	4	8	4.8	10	7.1	12	8.6
15	3	8	1.4	Died	-	Died	-
16	4	8	2	8	3.7	Died	-
17	3	8	3.4	16	10	12	21.4
18	1	10	4.3	20	13.4	14	24
19	3	8	2.2	10	8.8	12	14.6
20	5	8	1.8	Died	-	Died	-

2. Literature Review of Salinity and Halophyte Models

A model of halophytic plant interactions with water quality and soil salinity that can address project objectives must model plant salt uptake, saline soil conditions, and water quality. Thus, the model is highly interdisciplinary, incorporating ecology, hydrology, soil science, and geochemistry. A physically-based and mechanistic model allows examination of model uncertainties, sensitivity, and causal implications. Because halophytic plants would potentially be cultivated on farmlands, they should ideally be modeled at a field scale first. The time scale should be large enough to handle a multi-year simulation because sufficient salt removal may take years. The model should be able to simulate irrigated crop growth, production, and harvesting. Because many halophytes are perennials, the model should be able to carry-over biomass from year to year. The model should be able to distinguish the main salt ions and track them through the soil-water-plant continuum because of toxicity effects and nutrient imbalances that cause plants to be negatively affected by high concentrations of soil salts. Finally, the model would ideally have an economic module for analyzing the financial viability of growing halophytes for ultimate use in addressing long-term project goals.

A literature review was conducted to find the most appropriate model for simulating salts and halophytes (Table 3). Currently, most models already developed to model salts do not address all project needs (i.e., not field scale, only model Na^+, etc.) or are solely empirical models. The more promising models that were examined include WATSUIT, CropSyst, BUDGET, ENVIRO-GRO and Agricultural Policy Environmental Extender (APEX).

WATSUIT was developed from the 1970s through the 1990s by Dr. Jim Oster from the University of California-Riverside, and Dr. James Rhoades from the US George Brown Salinity Laboratory (Wu 2002). This model is a steady-state computer model that is used to evaluate irrigation water suitability. WATSUIT assumes that a leaching fraction is constant over time (i.e., cation exchange reactions are assumed to be at equilibrium). This model differentiates between major cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) and anions (Cl^-, HCO_3, CO_3^{2-}, and SO_4^{2-}) in irrigation water. WATSUIT calculates concentrations of these major ions in soil water based on the composition of irrigation water and the management practices that are being used. Depth of the rootzone is not defined, but is assumed to be constant. The model does not simulate crop growth or include salt movement through plants. WATSUIT is written so that the effects of adding sulfuric acid and gypsum to irrigation water can be modeled.

CropSyst is a Food and Agriculture Organization (FAO) model aimed at evaluating best management practices (Stockle et al. 1993). When determining the best management options, it incorporates weather, soil characteristics, field hydrology, crop characteristics, crop rotation, residue levels, and other factors. This model builds itself off of the Erosion-Productivity Impact Calculator (EPIC). Its water budget is detailed, with components including interception, runoff, infiltration, redistribution, crop potential evapotranspiration (ET), actual ET, and soil evaporation. This model can simulate nitrogen transport through the soil profile, as well as crop growth (Stockle et al. 1993). CropSyst has been modified to assess crop response and water management in saline conditions (Ferrer and Stockle 1996). The model includes the osmotic effect of salinity in the existing water uptake term, and also a function for salinity effects on root permeability. This model does not assume a steady-state condition for soil. Richard's equation is used for water transport, and a convective equation is used for solute transport. Crop growth is dependent on the water uptake term which has been modified in the model to account for soil salts. Other factors and management practices such as a shallow water table, irrigation scheduling, and water quality can also be analyzed in this model (Ferrer and Stockle 1996).

Table 3: Models included in the literature review and metrics for choosing the most suitable model. ~X in the management column indicates that it could only model irrigation.

Model	Models Plants	Models Salinity	Differentiates Salt Ions	Mechanistic Model	Models Management	Econ-omics
WATSUIT		X	X	X	~X	
CropSyst	X	X		X	X	X
BUDGET	X	X		X	~X	
APEX	X	X		X	X	X
Yadav (2005)	X	X		X	X	
Shani et al. (2007)	X	X		X		
Maas (1993)	X	X				
Jalali and Homaee (2010)		X		X		
Schleiff (2006)	X	X				
ENVIRO-GRO	X	X		X	X	

BUDGET describes the processes involved in water extraction by plant roots and water movement in the soil profile (Raes and Leuven 2002). This program is suitable for assessing crop water stress under rainfed conditions, estimating yield responses to water, designing irrigation schedules, studying salt accumulation in the root zone by irrigation, and evaluating irrigation management practices. This model requires climatic data inputs in daily, 10-day or monthly time scales, crop parameters, soil parameters, irrigation data, and the initial soil water and salt conditions in the soil profile. Crop parameters include the class of crop type, rooting depth, degree of ground cover at the maximum crop canopy (sparse to dense), and the length of the growing period. Model output includes the final soil moisture profile, the final salt content of the soil water, the expected crop yield, and the irrigation water requirement. In the model, salt comes into the system only through irrigation water (Raes and Leuven 2002).

ENVIRO-GRO was developed in the 1990s by the University of California Division of Agriculture and Natural Resources. The model is meant to simulate the growth of agricultural crops, subsurface variably-saturated water flow, solute transport, root water uptake, nitrogen uptake, and relative crop field. The model was initially a one-dimensional, transient-state model of subsurface water flow and chemical transport. Nitrogen subroutines have been added, enabling the model to simulate nitrate transport and nitrogen uptake by plants and production of nitrate by organic nitrogen mineralization, and compensation for root water and nitrogen uptake. The model is very theoretically based. ENVIRO-GRO models the negative impact that salt stress can have on crop yield, but is not capable of modeling salt through the soil-plant-water interface. ENVIRO-GRO does not contain an economic subroutine (Letey and Vaughan 2013).

APEX is a widely-used multi-scale model that is based on the Environmental Policy Integrated Climate (EPIC) model (Sharpley and Williams 1991). This model is intended to be used for managing whole farms or small watersheds to sustain environmental quality and achieve sustainable production (Steglich and Williams 2008). APEX uses a daily time step, but is capable of multi-year simulations of more than 1000 years (Steglich and Williams 2008). The model is written in Fortran and includes 12 major components including climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion and sedimentation, carbon cycling, management practices, soil temperature, plant environment control, economic budgets, and subarea/channel routing (Gassman et al. 2010). APEX is capable of simulating a variety of management techniques such as irrigation, drainage, crop rotation and selection, biomass removal, and grazing (Gassman et al. 2010). This model is also capable of evaluating interactions between surface runoff, return flow, sediment deposition, land degradation, nutrient transport and groundwater flow. The model simulates the fate and transport of nutrient and contaminants in subareas and through channel networks in terms of nitrogen, phosphorous, carbon, and pesticide losses (Gassman et al. 2010). Livestock grazing, manure management, and manure erosion are also included (Gassman et al. 2010). At the beginning of this project, APEX was able to model total EC in soil water, runoff, and leaching, but was not able to model upward movement of salt by evaporation or plant uptake or differentiate ions.

Based on the literature review, it was determined that APEX was best suited for this project. WATSUIT was not applicable because it was incapable of modeling salt movement and its impact on plants, and it could only model irrigation management. BUDGET was not appropriate because it also could only model irrigation management. ENVIRO-GRO was not selected because it does not have an economics module, which will be important for future iterations of this project. CropSyst and APEX were similar in their abilities. Both of these models can model plants, salinity, management, and economics, but neither could differentiate ions. APEX was selected for the current project because APEX was modified to include a salinity module that enabled plants to take salt out of the soil.

Climate input data for APEX include precipitation, minimum and maximum temperature, solar radiation, wind speed and relative humidity on a daily time step. Climate data can be entered from recorded measurements, can be generated by the model, or can be provided in combinations of recorded and generated data. Climate data generations use a first-order Markov Chain model for precipitation, a multivariate generation approach for air temperature and solar radiation, the Wind Erosion Continuous Simulation (WECS) model for wind, and a triangular distribution from tabulated average monthly values for average relative humidity.

Crop growth uses only one module within APEX to simulate crops, trees, and other plants. Up to 10 competitive plants can be simulated in one area using the Agricultural

Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model, whose algorithms are included as an arm of the APEX family that focuses on crop and plant parameters. Both perennials and annuals can be modeled with phenological crop development based on daily heat unit accumulation. For example, annuals grow from planting until harvesting unless accumulated heat units equal potential heat units for that particular plant. Perennial crops can be simulated for several years, becoming dormant after frost until the average daily air temperature is greater than the plant's base temperature for growth (Steglich and Williams 2008).

The hydrologic balance in APEX incorporates key aspects of the hydrologic cycle including precipitation, interception, melt water, groundwater, and runoff. Precipitation, melt water, and irrigation are separated into surface runoff and infiltration. Infiltrated water can either move vertically and be lost to evapotranspiration or move laterally and become drainage flow. Groundwater can interact with stream channels and off-site effects. Surface runoff volume and peak runoff rate are estimated in APEX. Peak runoff rate caused by rainfall, snowmelt, or irrigation is used to calculate erosion loss. Both horizontal and vertical flow are used to calculate subsurface flow which uses storage routing and pipe flow equations. Soil parameters such as maximum soil water holding capacity, saturated conductivity and porosity are used to estimate vertical percolation of infiltrated water. This routing process continues until water reaches the water table. Groundwater can lose water through return flow to stream channels or to deep percolation. Horizontal flow is classified as either lateral or quick return flow. The APEX model has options for calculating potential evaporation, including Penman-

Monteith (default), Penman, Priestley-Taylor, Hargreaves, and Baier-Robertson. Penman-Montieth was chosen because of its simplicity. The different methods require varied information including solar radiation, air temperature, wind speed, and relative humidity (Gassman et al. 2010).

In order for APEX to be suitable for modeling halophytes, a salinity module needed to be added because the model did not follow salts through the soil-water-plant interface (Rossi 2012). Dr. Jaehak Jeong coded the salinity algorithms with help from Dr. Cole Rossi in February 2014.

In the completed salinity module, an additional parameter was added to the crop database (SLTY) to indicate the fraction of biomass that is salt. This parameter allows salt to be taken out of the soil and water system with the crops. Another parameter added in the module is USLT1, or actual salt uptake by a crop (kg/ha) which is a function of the crop (CropID) and the subarea (SA). Salt upward movement between the layers caused by evapotranspiration is also modeled. The upward movement of salt is simulated analogous to nitrate movement by multiplying the concentration of salt by the amount of water moving upward. Upward movement of salt is given as:

$$WSLT(i,SA) = WSLT(i,SA) - \Delta WSLT(i,SA) + \Delta WSLT(i+1,SA) \tag{5}$$

where ‘i’ is the soil layer number, SA is the subarea number, and WSLT is the salt in the soil layer in kg/ha. The term ΔWSLT(i,SA) is nonexistent for the first soil layer, and ΔWSLT(i+1,SA) is nonexistent for the bottom soil layer.

If the total salt in a layer is greater than the salt demand of the plant, then:

$$USLT1_t = USLT1_{t-1} + salt\ uptake * \frac{salt\ demand}{total\ salt} \tag{1}$$

where t is the time step. APEX uses a daily time step. If the total salt in a layer is less than the salt demand of the plant, then:

$$USLT1_t = USLT1_{t-1} + WSLT(i) \tag{2}$$

where salt demand is defined as:

$$Salt\ demand = SLTY * biomass - USLT1 \tag{3}$$

Total salt is defined as:

$$total\ salt = \sum_i WSLT(i) \tag{4}$$

3. Methods

3.1 Selection of Halophytic Plants to Model

To fit within the scope of this project, 2-4 halophytes were chosen to be modeled based on the amount of literature available for each plant, the growth form of the plant (similar growth forms for better comparison), whether the PEER project had selected that particular plant to be field tested, and the potential of the plant to support future research proposals. A literature review was conducted on all of the halophytes being field tested in Uzbekistan in the PEER project as well as several other halophytes that grow in the Great Basin that were suggested by Dr. Bob Nowak at the University of Nevada, Reno (Table 4). Crops that also grow in the Great Basin are included because the results of this research could help the salt affected agriculture in this region as well. The literature review found published parameters for the halophytes such as growth rates, responses to salt, biomass, water requirements, evapotranspiration rates, germination rates, responses to management, and salt control mechanism. These are parameters that are either already important for modeling crops in the APEX model (i.e., growth rates, biomass, or water requirements) or they are important to how plants respond to salinity.

Literature available for each plant was summarized with a weighted scale based on the number and quality of literature sources. Each parameter included in the literature review was given a weight dependent on the importance of the parameter to the project and as input into APEX (Table 5).

Table 4: Table of plants included in the literature review that shows why they were included (PEER project or suggested by Dr. Nowak), their growth form, and the number of literature sources found for each plant. Blank spaces for growth form indicate that growth form was unable to be determined.

Plant	Reason for inclusion		Growth form	# sources
	PEER project	Nowak		
Atriplex canescens		X	Perennial shrub	4
A. confertifolia		X	Perennial shrub	1
A. hymenelytra		X	Perennial shrub	0
A. nitens (A.hortensis)	X		Annual herb	6
Climacoptera lanata	X		Annual herb	5
Distichlis spicata	X	X	Perennial grass	7
Glycyrrhiza glabra			Perennial shrub	3
Helianthus tuberosus	X		Perennial herb	5
Kalidium caspia	X			6
Pennisetum glaucum (Pearl millet)	X		Annual grass	2
Salicornia bigelovii		X	Annual herb	2
Salicornia europeae	X		Annual herb	7
Sorghum bicolor	X		Annual grass	7
Suaeda altissima	X		Annual herb	3
Suaeda paradoxa	X			0

Table 5: Weights assigned to each parameter included in the literature review. 0 =not important, 5 = essential

Parameter	**Weight**
Growth Rates	4
Responses to Salt	5
Biomass	4
Nutritive Value	1
Biofuel Potential	1
Economic Value	1
Water	4
Management	4
Climate (temperature, precipitation)	3
Soils	3
GW Quality	3
Wind Speed	2
Solar Radiation	2
Strategy Type	3
Evapotranspiration	3
Germination Rates	4

Weights ranged from 0 = unimportant to 5 = imperative to the research. Nutritive value, biofuel potential, and economic value were weighted with 1 because, whereas the utility of these plants is important for the long-term goals of this research, it was not important in determining whether the plants and salt dynamics can be modeled. Groundwater quality, wind speed, and solar radiation were given a weight of 2 because, whereas these parameters are important to modeling halophytes, they are site specific, and the data for these were collected near model sites. Climate (precipitation and minimum and maximum daily temperature) and evapotranspiration were given a weight of 3 because these are important in modeling and parameterizing plants. Halophyte strategy type was also given a weight of 3 because how halophytes deal with salts could be an important indicator of plants that are good for salt phytoremediation. Plant growth rates, plant biomass, water, management, and germination rates were given a weight of 4 because they are important parameters for modeling halophytes. Responses to salt were given a weight of 5 because of its importance for assessing the utility of halophytes. Salt responses found in literature varied greatly. They primarily included how plant biomass (dry weight) changes with different water salinity, and how relative growth rate, cation (Na^+, K^+, Ca^{2+}, Mg^{2+}) contents of the plant, and K^+-Na^+ selectivity ratios change with increasing salinity. Measured salinity was generally reported in units of mass per volume or as electric conductivity in units of electrical resistance per length (typically dS/m).

Plant species were ranked according to the weighted score calculated for each halophyte (Table 6). The life form that had the highest weighted score was the annual herbs. Two annual herbs were selected for modeling so that they could be compared without as many uncertainties as with comparing different life forms. Annual plants are better choices to model because there is no biomass carryover from year to year. Thus, we decided to model at least two annual herbs to assess model performance. Plants selected for parameterization into the APEX model were *A. nitens, S. europeae,* and *C. lanata* (Figure 14). *Atriplex nitens* and *S. europeae* were chosen because they scored best in the literature review and they are both annual herbs. *Salicornia europeae* was dropped from cultivation in the PEER project because of its low biomass production and limited amount of seeds. However, it was selected for modeling because of the amount of literature available and its remarkable salinity tolerance. It also grows wild near the Uzbek Kyzylkesek field site in a solonchak. The Uzbek team collected samples of wild *S. europeae* and measured nearby soil and water conditions throughout the growing season. *Climacoptera lanata* is also an annual herb and was modeled despite not growing in North America because of its importance as valuable forage for animals in the Kyzylkum desert.

Table 6: Rankings of plants included in the literature review. Plants selected for modeling are highlighted.

Rank	Score	Plant	In PEER Study?	Life Form
1	53.5	*Atriplex nitens (A. hortensis)*	yes	Annual herb
2	49.6	*A.canescens*	no	Perennial shrub
3	49.2	*Salicornia europeae*	yes	Annual herb
4	41.3	*Distichlis spicata*	yes	Perennial grass
5	41.2	*Helianthus tuberosus*	yes	Perennial herb
6	40.0	*Kalidium caspia*	yes	
7	37.8	*Sorghum bicolor*	yes	Annual grass
8	28.2	*Climacoptera lanata*	yes	Annual herb
9	21.8	*Glycyrrhiza glabra*	yes	Perennial shrub
10	16.3	*Salicornia bigelovii*	no	Annual herb
11	16.0	*Pearl millet (Pennisetum glaucum)*	yes	Annual grass
12	12.0	*Suaeda altissima*	yes	Annual herb
13	11.0	*Atriplex confertifolia*	no	Perennial shrub

Currently in Uzbekistan, *S. europeae* is used for soda-based glassmaking and soapmaking (Toderich 2013). It has some forage value, but in limited amounts because of its high salt content. *Climacoptera lanata* is a valuable food source for sheep, goats, and camels, usually in autumn or winter. It has some use for rehabilitation of sandy and saline waterlogged areas. *Atriplex nitens* has forage value for sheep, goats, and camels (Toderich 2013b). *Atriplex nitens* and *C. lanata* are ion excretion halophytes, and *S. europeae* is a salt succulent halophyte.

Medicago sativa (alfalfa) was chosen to be modeled as a control crop (Figure 14). *Medicago sativa* is a glycophyte that is being used as the control crop in the PEER project. It is already included in the APEX database.

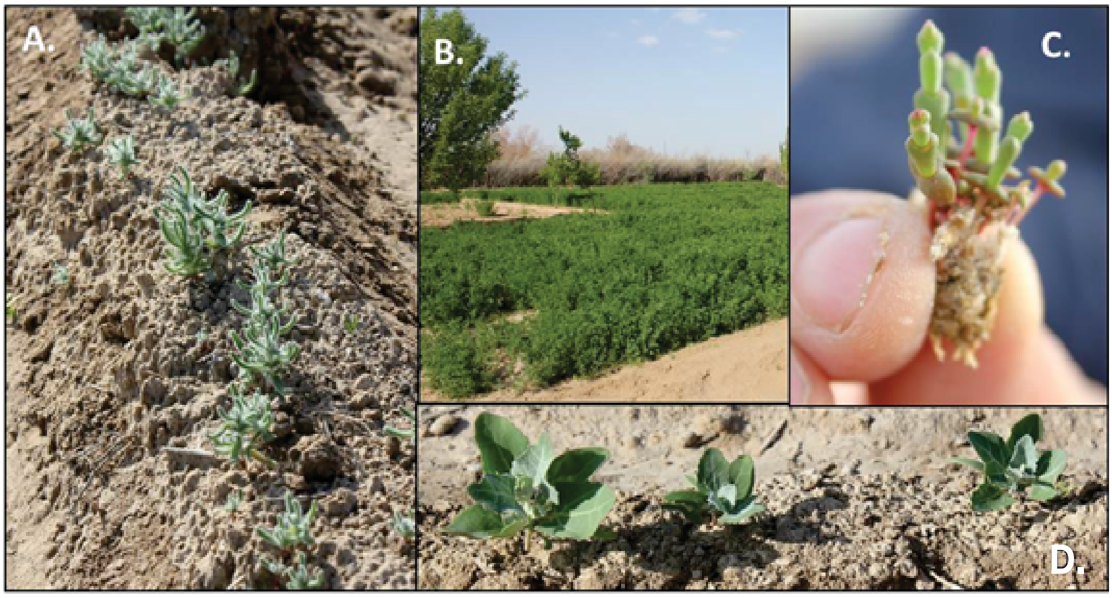


Figure 14: A) *Climacoptera lanata* **B)** *Medicago sativa* **C)** *Salicornia europeae* **and D)** *Atriplex nitens* **in the Kyzylkezek location in April 2013.**

3.2 Parameterization of Uzbek Field Sites

APEX uses Excel tables for each set of parameters such as weather, soil, location, and other control parameters (Table 7). The halophytes *A. nitens*, *S. europeae*, and *C. lanata* were parameterized and added into the model database. Field site data were also added, including soil and climatic data and the locations. The sites must be further parameterized based on management techniques in Uzbekistan.

Table 7: APEX data tables for necessary site information and parameters

Data Table	Parameters
Location Table	Latitude, longitude
Weather Stations	Min/max temperature, precipitation (number of days, amount, probability wet day follows wet or dry day), relative humidity, average monthly wind speeds
Soils Data	Sand content, silt content, initial organic N concentration, soil pH, cation exchange capacity, dry bulk density, etc.
Control Table	Simulation duration (years), fertilizer/pesticide application, field size, irrigation water quality, etc.

3.2.1 Halophytes

The plants *C. lanata*, *S. europeae*, and *A. nitens* are not conventional crops, so they were not already included in the APEX database. Every plant in the APEX database has 56 parameters (Appendix A). Most of these parameters had not been previously described in the literature for halophytes. With the help of Dr. Jim Kiniry with the USDA-ARS, crops similar to selected halophytes were used to provide initial values for crop parameters. Some of these initial parameter values were changed if data were available for that parameter in the literature, if Dr. Kiniry suggested a different value, or if necessary to be similar to other halophytes (Table 8). Initial values for *A. nitens* were taken from *Spinacia oleracea*, or spinach (Table 9). The common name for *A. nitens* is mountain spinach, and the two plants are visually similar. Initial values for *S. europeae* were taken from *Asparagus officinalis*, or asparagus (Table 10) because *S. europeae* and *A. officinalis* both have large fleshy stems and grow to be similar sizes. Initial values for *C. lanata* come from a species of *Cedrus*, or cedar (Table 11) because of visual similarities. Cedar is parameterized in ALMANAC but not APEX, so the ALMANAC parameters were added into APEX. Since *Cedrus* is a perennial tree and not an annual herb, many more parameters had to be changed for *C. lanata* than for the other two halophytes. Some *C. lanata* parameters were changed from *Cedrus* by examination of photos of the two plants to make them consistent with parameters for other annual herbs.

Table 8: Definitions and units of parameters that were changed for the 3 modeled halophytes.

Parameter	Units	Definition
HI	none	Harvest index (Harvestable yield : total biomass)
DMLA	ratio	Maximum potential leaf area. (Leaf surface area : area of ground covered by plants)
HMX	m	Maximum crop height
RDMX	m	maximum root depth
CPY	g/g	Fraction of phosphorus in yield
CKY	g/g	Fraction of potassium in yield
WSYF	none	Lower limit of harvest index. Between 0 and HI
WCY	g/g	Fraction of water in yield
IDC	none	Crop category number
RWPC1	fraction	Fraction of root weight at emergence
RWPC2	fraction	Fraction of root weight at maturity
GMHU	days	Heat units required for germination
PPLP1	none	Plant population for crops and grass. 1st point on curve
PPLP2	none	Plant population for crops and grass. 2nd point on curve
BLG1	fraction	Lignin fraction in plant at 0.5 maturity
BLG2	fraction	Lignin fraction in plant at full maturity
WUB	t/mm	Water use conversion to biomass

Table 9: Documented parameter changes for *Atriplex nitens* based on *Spinacia oleracea*

Parameter	*S. oleracea*	*A. nitens*	Source
HI	0.95	0.99	Jim Kiniry
DMLA	4.2	3.0	Jim Kiniry
HMX	1.200	1.854	Toderich et al. (2009)
RDMX	0.7	0.5	Jim Kiniry
CPY	0.0058	0.0060	Wilson et al. (2000)
CKY	0.0663	0.0588	Wilson et al. (2000)
WCY	0.92	0.53	Toderich et al. (2009)
RWPC2	0.20	0.13	Kachout et al. (2009)

Table 10: Documented parameter changes for *Salicorni. europeae* based on *Asparagus officinalis*

Parameter	*A. officinalis*	*Salicornia europeae*	Source
HI	0.80	0.99	Jim Kiniry
DMLA	4.2	1.5	Jim Kiniry
HMX	1.20	0.16	Jim Kiniry
RDMX	1.5	1.0	Jim Kiniry
CKY	0.0390	0.0216	Akinshina et al. (2012)
WCY	0.92	0.92	Lv et al. (2012)

Table 11: Documented parameter changes for *Climacoptera. lanata* based on *Cedrus*

Parameter	*Cedrus*	*Climacoptera lanata*	Source
HI	0.01	0.99	Jim Kiniry
DMLA	12.0	4.5	Jim Kiniry
HMX	12.000	0.762	Toderich et al. (2009)
RDMX	3.5	1.0	Shortened roots because it is not a tree
CKY	None	0.02157	Akinshina et al. (2012)
WYSF	0.0	0.8	Given some drought tolerance. Same as *S. europeae*
WCY	0.01	0.76	Toderich et al. (2009)
IDC	7	5	Observation—it is a cold weather annual
WAVP	None	7	Median of the range given in user manual (6-8)
RWPC1	None	0.4	Changed to be consistent with other annual herbs
RWPC2	None	0.2	Changed to be consistent with other annual herbs
GMHU	None	100	Changed to be consistent with other annual herbs
PPLP1	2.22	10.20	Changed to be consistent with other annual herbs
PPLP2	9.99	50.90	Changed to be consistent with other annual herbs
BLG1	None	0.01	Changed to be consistent with other annual herbs
BLG2	None	0.1	Changed to be consistent with other annual herbs
WUB	None	0	Changed to be consistent with other annual herbs

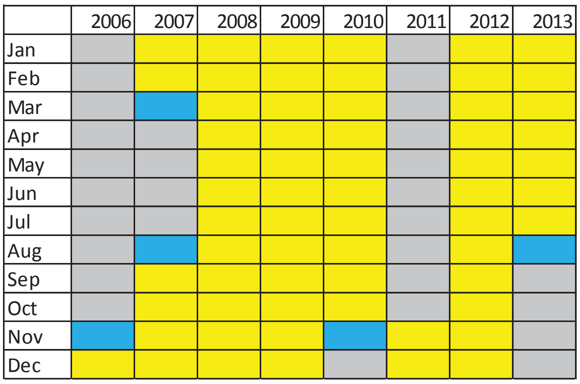
3.2.2 Weather

APEX can run simulations with daily weather input over a given time period, or it can simulate weather based on monthly statistics for days with rain, precipitation, probability that a wet day follows a dry day, probability that a wet day follows a wet day, solar radiation, relative humidity, standard deviation of minimum temperature, standard deviation of maximum temperature, standard deviation of precipitation, skew coefficient for precipitation, average minimum temperature, and average maximum temperature. Ideally, APEX would be run with actual daily weather data for the modeled year when plant data were available. However, because most weather data from Uzbekistan for 2013 was discontinuous (Table 12, 13), the weather generator option was used. When using the weather generation option, APEX created a weather pattern for 2013 that was used for all runs. Solar radiation was generated using the given site latitude rather than monthly statistics.

Table 12: Months of available data in Khorezm. Yellow indicates complete daily weather data, blue indicates partial daily weather data, and grey indicates no weather data available.

	2005	2006	2007	2008	2009	2010	2011	2012	2013
Jan	🟨	🟨	⬜	🟨	🟦	🟨	🟦	🟦	🟦
Feb	🟨	🟨	🟦	🟨	🟨	🟨	⬜	🟦	🟨
Mar	🟨	🟦	🟨	🟦	🟨	🟨	🟦	🟦	🟨
Apr	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨
May	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Jun	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦
Jul	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Aug	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦
Sep	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬜
Oct	🟨	🟨	🟨	🟨	🟦	🟨	🟨	🟨	⬜
Nov	🟨	🟨	🟨	⬜	🟨	🟨	🟦	🟨	⬜
Dec	🟨	🟦	🟨	⬜	🟨	🟨	🟦	🟦	⬜

Table 13: Months of available data in Kyzylkezek. Yellow indicates complete daily weather data, blue indicates partial daily weather data, and grey indicates no weather data available.



	2006	2007	2008	2009	2010	2011	2012	2013
Jan	⬜	🟨	🟨	🟨	🟨	⬜	🟨	🟨
Feb	⬜	🟨	🟨	🟨	🟨	⬜	🟨	🟨
Mar	⬜	🟦	🟨	🟨	🟨	⬜	🟨	🟨
Apr	⬜	⬜	🟨	🟨	🟨	⬜	🟨	🟨
May	⬜	⬜	🟨	🟨	🟨	⬜	🟨	🟨
Jun	⬜	⬜	🟨	🟨	🟨	⬜	🟨	🟨
Jul	⬜	⬜	🟨	🟨	🟨	⬜	🟨	🟨
Aug	⬜	🟦	🟨	🟨	🟨	⬜	🟨	🟦
Sep	⬜	🟨	🟨	🟨	🟨	⬜	🟨	⬜
Oct	⬜	🟨	🟨	🟨	🟨	⬜	🟨	⬜
Nov	🟦	🟨	🟨	🟨	🟦	🟨	🟨	⬜
Dec	🟨	🟨	🟨	🟨	⬜	🟨	🟨	⬜

Available data from the Khorezm region included daily average, minimum, and maximum air temperature, average wind direction, precipitation, and average wind speed from January 2005 through August 2013. These data were used to calculate necessary weather statistics. Months with no or incomplete climate data were not included in calculating monthly averages.

Kyzylkezek data included wind speed, precipitation amount, 3 independent readings of air temperature, and relative humidity in 10 minute increments from November 2006 through August 2013. Data were aggregated into average daily data for daily average maximum and minimum temperatures, relative humidity, and wind speed. Precipitation data were aggregated into daily total precipitation.

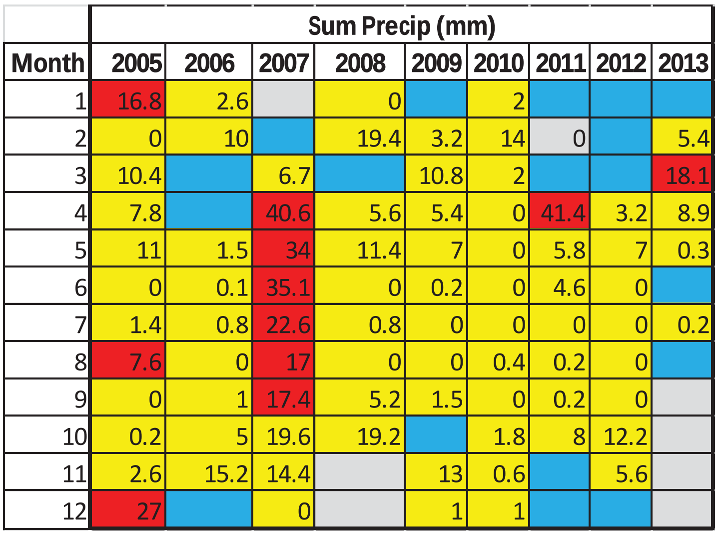
For both Kyzylkezek and Khorezm, the number of days with rain, probability that a wet day follows a dry day, and the probability that a wet day follows a wet day were calculated with a series of Boolean values (Appendix B). For both locations, the amount of precipitation was summed for each valid month in each year. The average, standard deviation, and skew of precipitation for a particular month in the data set were calculated.

In the Khorezm region, several months of precipitation appeared to be outliers that could have large impacts on overall precipitation statistics (precipitation amount, standard deviation, skew, and the probabilities) because the data set included fewer than 10 years of data. For this reason, an Interquartile Range (IQR) outlier test was used to identify months that were outliers. This method was chosen because it does not assume that data are normal. The IQR is the difference between values that correspond with the third and first quartiles (Navidi 2011). Seventy-five percent of the data are less than the third quartile, and 25% of the data are less than the first quartile. A value is considered to be an outlier if it is 1.5*IQR greater than the third quartile or 1.5*IQR less than the first quartile. Using this method, 11 months were identified as outliers (Table 14), but these months were not necessarily thrown out. Since most outlier months occurred in 2007, all months in that year were neglected in calculating precipitation statistics. April 2011 and 2007 were also not included in statistic calculations because of the unreasonably large precipitation amount compared to other months. The remaining outlier months were left in the dataset.

Relative humidity and wind speed were calculated by taking the average relative humidity for each month in each year (Tables 15 and 16). Average minimum and maximum temperatures were calculated by averaging the minimum and maximum temperatures for each day in each month over all years. Standard deviations for minimum and maximum temperatures were calculated for each month in each year. Only data from complete months were used.

APEX requires the probability that wind comes from a certain direction. Wind direction was not measured at the Kyzylkezek site, so wind direction data for the Khorezm station were used for both sites because it is highly variable and difficult to estimate (Table 17). Furthermore, if a wind station is not selected for a site in APEX, the closest wind station will be used and all other wind stations that already exist in APEX are in Texas, USA.

Table 14: Months found to be outliers (red), months with complete data (red and yellow), months with incomplete data (blue), and months with no climatic data (grey) in Khorezm.



	Sum Precip (mm)								
Month	2005	2006	2007	2008	2009	2010	2011	2012	2013
1	16.8	2.6	⬜	0	🟦	2	🟦	🟦	🟦
2	0	10	🟦	19.4	3.2	14	0	🟦	5.4
3	10.4	🟦	6.7	🟦	10.8	2	🟦	🟦	18.1
4	7.8	🟦	40.6	5.6	5.4	0	41.4	3.2	8.9
5	11	1.5	34	11.4	7	0	5.8	7	0.3
6	0	0.1	35.1	0	0.2	0	4.6	0	🟦
7	1.4	0.8	22.6	0.8	0	0	0	0	0.2
8	7.6	0	17	0	0	0.4	0.2	0	🟦
9	0	1	17.4	5.2	1.5	0	0.2	0	⬜
10	0.2	5	19.6	19.2	🟦	1.8	8	12.2	⬜
11	2.6	15.2	14.4	⬜	13	0.6	🟦	5.6	⬜
12	27	🟦	0	⬜	1	1	🟦	🟦	⬜

Table 15: Monthly climate statistics calculated for the Khorezm region

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Days with rain	days	3.50	4.33	4.75	3.00	3.25	0.71	0.75	1.00	1.14	3.00	4.00	5.33
Precipitation	mm	5.35	8.67	10.33	5.15	5.50	0.70	0.40	1.17	1.13	7.73	8.57	7.25
Prob wet following dry		0.08	0.09	0.14	0.08	0.10	0.02	0.02	0.02	0.02	0.09	0.11	0.12
Prob wet following wet		0.36	0.50	0.21	0.29	0.12	0.20	0.00	0.29	0.38	0.17	0.30	0.44
Relative humidity		0.82	0.78	0.67	0.52	0.46	0.44	0.50	0.55	0.55	0.62	0.71	0.77
St dev (min temp)	˚C	8.69	8.12	1.96	3.28	2.05	5.88	1.00	1.45	1.67	1.51	1.97	3.34
St dev (max temp)	˚C	5.69	2.40	2.77	4.46	1.00	1.00	1.15	3	3.31	2.10	4.80	5.31
St dev precipitation	mm	0.52	0.99	1.03	1.10	0.57	0.09	0.06	0.12	0.17	0.90	0.84	1.08
Skew coefficient (precip)		4.48	4.00	3.73	4.11	4.15	4.93	5.07	5.26	4.84	4.02	4.53	4.03
Temp min	˚C	-13.37	-15.22	-3.67	1.93	8.72	11.08	14.60	12.47	6.10	-0.32	-6.38	-14.15
Temp max	˚C	10.35	14.18	27.07	33.10	36.23	39.48	41.80	41.13	35.54	29.58	22.33	13.93

Table 16: Monthly climate statistics calculated for the Kyzylkezek region

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Days with rain	days	4.67	7.38	6.20	4.34	2.60	0.83	0.20	0.25	0.21	1.40	2.89	5.67
Precipitation	mm	8.67	22.50	20.08	13.50	5.30	5.00	1.30	0.20	0.90	4.60	8.80	9.58
Prob wet following dry		0.11	0.14	0.17	0.12	0.07	0.03	0.01	0.01	0.01	0.02	0.09	0.13
Prob wet following wet		0.39	0.55	0.32	0.24	0.23	0.00	0.00	0.00	0.00	0.57	0.14	0.44
Relative humidity		0.85	0.81	0.67	0.56	0.35	0.24	0.21	0.21	0.27	0.43	0.74	0.84
St dev (min temp)	˚C	7.01	6.41	3.99	2.21	2.74	2.35	2.02	2.92	9.57	7.73	4.47	5.10
St dev (max temp)	˚C	5.40	2.67	3.91	2.96	2.98	2.02	1.61	2.09	3.46	3.19	4.74	4.70
St dev precipitation	mm	0.91	1.90	1.96	1.36	0.60	0.60	0.23	0.04	0.16	0.52	1.12	0.81
Skew coefficient (precip)		3.69	3.50	3.37	4.02	4.26	4.27	5.57	5.57	5.48	4.83	4.45	3.26
Temp min	˚C	-24.01	-17.10	-1.97	4.36	11.18	16.66	18.48	17.15	8.28	-0.03	-6.65	-14.76
Temp max	˚C	13.19	13.66	24.50	30.90	35.09	40.70	42.00	41.50	35.21	28.58	20.96	12.44

Table 17: Monthly probabilities in percent for wind direction in the Khorezm region

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Jan	0	0	1	2	6	8	17	16	27	15	2	3	1	2	0	0
Feb	0	0	0	3	4	10	11	21	30	14	3	2	1	0	0	0
Mar	0	0	0	3	8	11	13	15	24	15	5	3	1	0	0	0
Apr	0	0	0	2	6	13	12	21	28	12	4	1	1	0	0	0
May	0	0	0	2	10	12	20	27	23	5	1	0	0	0	0	0
Jun	0	0	0	6	10	21	24	26	10	1	1	0	0	0	0	0
Jul	0	0	3	7	14	24	21	21	9	1	0	0	0	0	0	0
Aug	0	0	0	10	21	19	22	15	5	2	1	3	1	0	0	0
Sep	0	0	1	3	5	20	27	19	13	3	3	2	3	3	0	0
Oct	0	0	1	2	5	12	19	25	21	6	5	2	1	0	0	0
Nov	0	0	0	4	3	5	18	26	26	8	6	1	1	0	0	0
Dec	0	0	0	2	5	4	10	19	42	10	4	4	1	1	0	0

Monthly averages for maximum and minimum daily air temperature and precipitation generated by APEX for Kyzylkezek and Khorezm are in Figures 15 and 16 respectively. This weather pattern was the same for every model run for Kyzylkezek and Khorezm in 2013. Dr. Toderich mentioned that 2013 seemed to be an average-weather year, and APEX generated average weather according to the calculated statistics (Figures 15, 16)

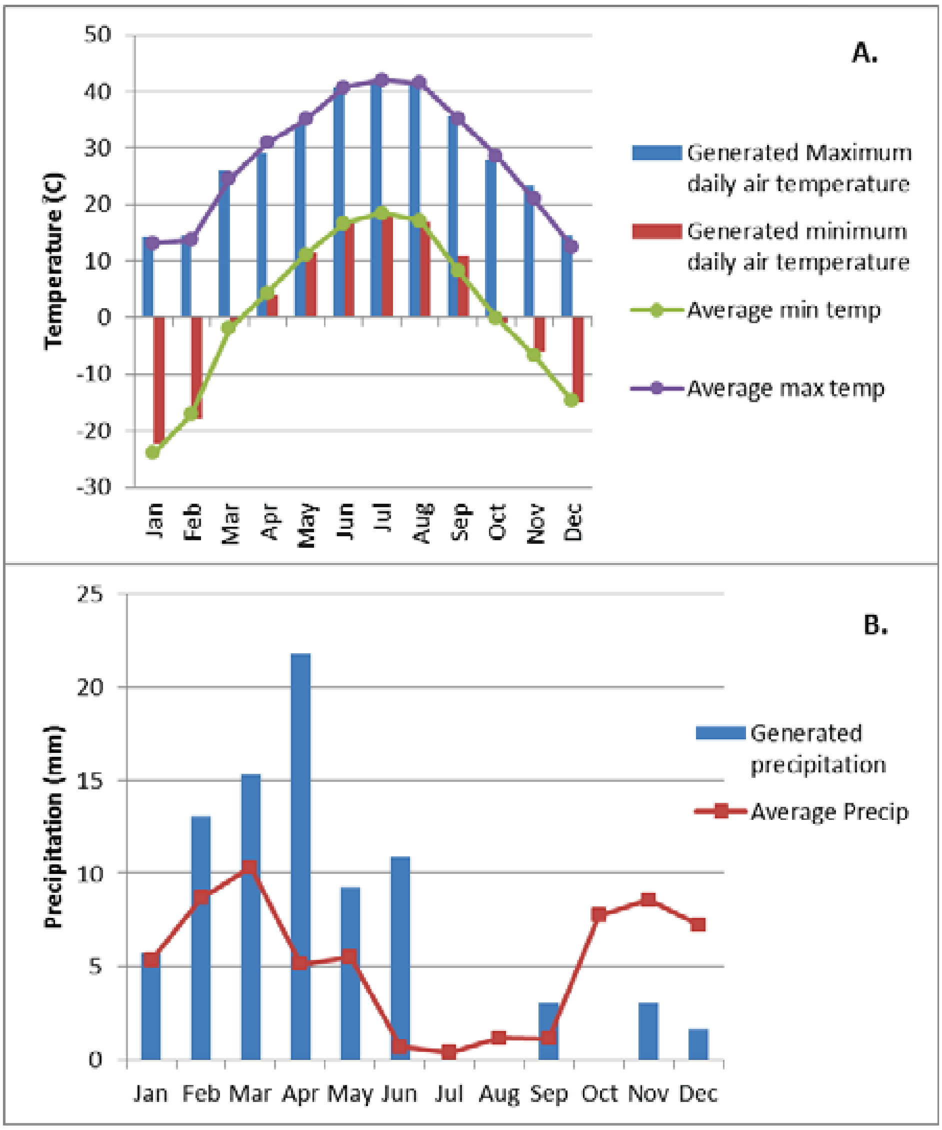


Figure 15: A) Temperature and B) precipitation generated by APEX for Kyzylkezek. Bars represent generated weather and the line indicates the calculated average min/max temperature or precipitation.

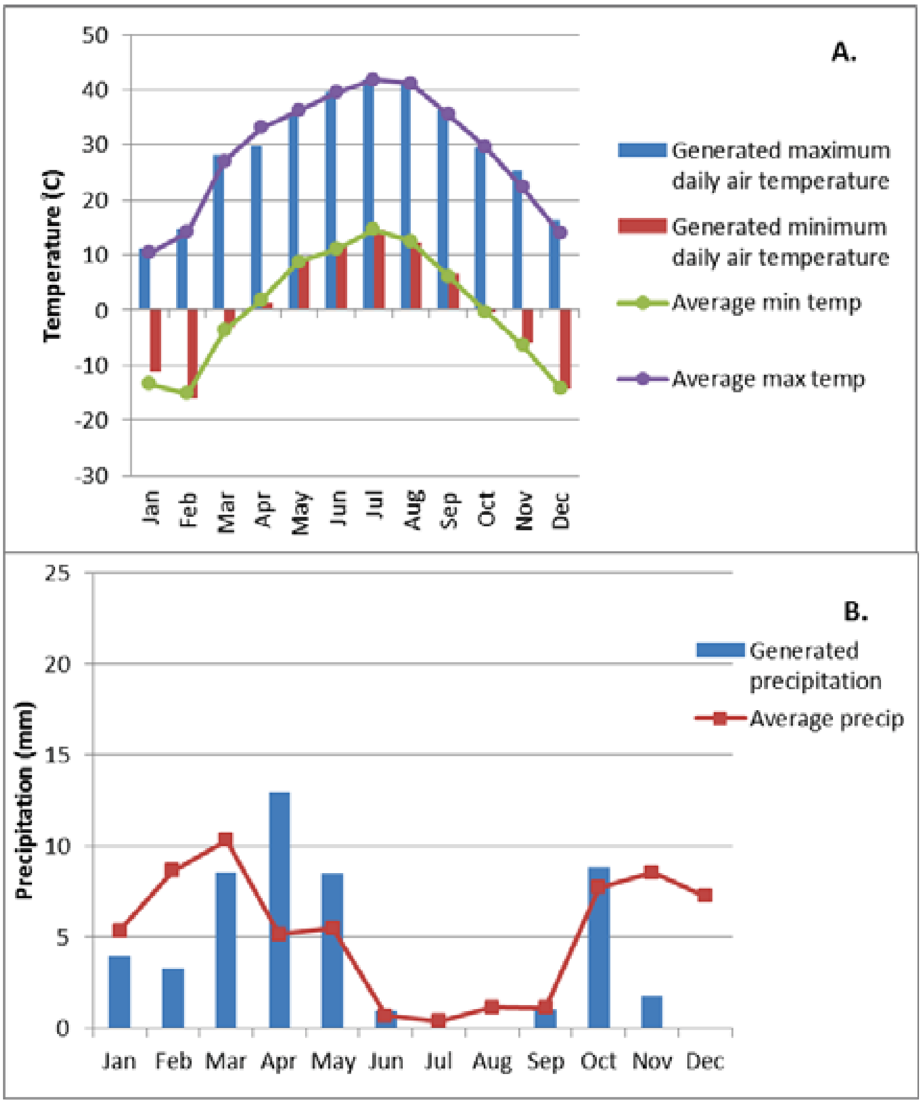


Figure 16: A) Temperature and B) precipitation generated by APEX for Khorezm. Bars represent generated weather and the line indicates the calculated average min/max temperature or precipitation.

3.2.3 Soil File

The soils database contains both a soil data table and a soil list table. The soil data table contains 31 parameters, 19 of which normally need to be specified and are relevant for the Uzbek sites (Table 18). Of these 19 parameters, only parameters Z, PH, ECND, CNDS, O, and K were directly measured in the field. Measured values for these soil parameters prior to planting input into the soil data file are in Tables 19, 20, 21, 22, and 23. The soil list table contains 7 parameters, 6 of which are relevant for the Uzbek field sites (Table 24). None of the parameters in the soil list table were directly measured in the field. Parameters not directly measured in the field and that did not have the option of being generated by APEX were filled in with ‘best guesses’ from personal observation of field sites by Dr. Michael Rosen. The ‘best guess’ parameters were included in model sensitivity analyses.

Table 18: Units and definitions of soil data parameters necessary for APEX models of Uzbek field sites

Parameter	Units	Definition
HYDGRP		Hydrologic soil group
Z	m	Depth to bottom of soil layer from soil surface
BD	g/cm^3	Moist bulk density
U	m/m	Soil water content at wilting point
FC	m/m	Soil water content at field capacity
SAN	fraction	Sand content
SIL	fraction	Silt content
PH		pH of soil
CBN	%	Organic carbon concentration
CEC	cmol/kg	Cation exchange capacity
BDD	g/cm^3	Dry bulk density
SC	mm/h	Saturated conductivity
ECND	fraction	Electrical conductivity
CNDS	g/Mg	Initial soluble N concentration
O	g/Mg	Initial labile phosphorus concentration
K	g/Mg	Initial K concentration

Table 19: Measured soil data table parameters for *M. sativa* at Kyzylkezek site on 3/1/2013 prior to planting. Soil layer depths are A (0-20 cm), B (20-40 cm), C (40-60 cm), D (60-80 cm), and E (80-100 cm).

Soil layer	CNDS (mg/kg)	O (mg/kg)	K (mg/kg)	pH	ECND (mS/cm)
A	6.10	9.85	345.55	7.59	1.53
B	4.15	5.15	156.55	7.66	0.50
C	4.40	5.00	138.45	7.68	0.31
D	4.15	3.80	132.45	7.69	0.29
E	3.25	10.05	174.60	7.63	0.35

Table 20: Measured soil data table parameters for *Atriplex nitens* at Kyzylkezek site on 3/1/2013 prior to planting. Soil layer depths are A (0-20 cm), B (20-40 cm), C (40-60 cm), D (60-80 cm), and E (80-100 cm).

Soil layer	CNDS (mg/kg)	O (mg/kg)	K (mg/kg)	pH	ECND (mS/cm)
A	21.40	48.30	582.70	7.51	1.57
B	15.13	20.99	391.82	7.58	0.78
C	15.56	17.76	360.87	7.60	0.81
D	15.96	14.64	355.74	7.61	3.82
E	11.40	49.28	294.43	7.55	0.36

Table 21: Measured soil data table parameters for *Climacoptera lanata* at Kyzylkezek site on 3/1/2013 prior to planting. Soil layer depths are A (0-20 cm), B (20-40 cm), C (40-60 cm), D (60-80 cm), and E (80-100 cm).

Soil layer	CNDS (mg/kg)	O (mg/kg)	K (mg/kg)	pH	ECND (mS/cm)
A	21.40	48.30	582.70	7.51	1.57
B	15.13	20.99	391.82	7.58	0.78
C	15.56	17.76	360.87	7.60	0.81
D	15.96	14.64	355.74	7.61	3.82
E	11.40	49.28	294.43	7.55	0.36

Table 22: Measured soil data table parameters for *Salicornia europeae* at Kyzylkezek site on 3/1/2013 prior to planting. Soil layer depths are A (0-20 cm), B (20-40 cm), C (40-60 cm), D (60-80 cm), and E (80-100 cm).

Soil layer	CNDS (mg/kg)	O (mg/kg)	K (mg/kg)	pH	ECND (mS/cm)
A	21.90	14.50	5.10	7.37	8.40
B	30.90	7.60	3.10	7.40	6.68
C	24.60	8.40	3.60	7.48	4.95
D	27.50	6.50	3.10	7.42	5.65
E	38.90	5.30	3.30	7.40	5.84

Table 23: Measured soil data table parameters for all crops at Khorezm site on 3/1/2013 prior to planting. Soil layer depths are A (0-20 cm), B (20-40 cm), C (40-60 cm), D (60-80 cm), and E (80-100 cm).

Soil layer	CNDS (mg/kg)	O (mg/kg)	K (mg/kg)	pH	ECND (mS/cm)
A	15.50	8.80	132.40	7.49	3.02
B	8.70	3.50	93.90	7.74	1.27
C	6.90	3.50	93.90	7.75	0.97
D	4.50	3.20	79.50	7.70	0.88
E	4.40	4.70	108.40	7.72	0.65

Table 24: Units and definitions of parameters in soil list table necessary for APEX models of Uzbek field sites.

Parameter	Units	Definition
lower slope (%)	%	lower slope of the soil
SALB	fraction	Soil albedo
WTMN	m	minimum depth to water table
WTMX	m	Maximum depth to water table
WTBL	m	Initial depth to water table

Parameters PH, ECND, CNDS, O, and K were measured in soil layers of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm from the surface. Dates of soil sampling and the number of soil layers measured for Kyzylkezek and Khorezm are in Tables 25 and 26, respectively.

Table 25: Number of soil layers sampled for each date and plant at Kyzylkezek site. "1" indicates only the top soil layer was sampled

Plant	8/11/2012	3/1/2013	4/14/2013	6/28/2013	8/4/2013
Atriplex nitens		1		1	
Climacoptera lanata		1	1		1
Salicornia europeae	5	5	1	1	
Medicago sativa	4	5			

Table 26: Number of soil layers that were measured for all crops on each date at Khorezm site. "1" indicates only the top soil layer was sampled.

Plant	9/15/2012	11/13/2012	3/1/2013	6/15/2013
All crops	5	5	5	1

Different soils with 5 layers each were parameterized for Khorezm and Kyzylkezek underneath *A. nitens*, for Kyzylkezek underneath *C. lanata*, for Kyzylkezek underneath *S. europeae* in the solonchak, and for Kyzylkezek underneath *M. sativa*. Measurements on

3/1/2013 were used to initialize soil parameters because it was the closest measurement day to crop planting.

Atriplex nitens and *C. lanata* only had measured soil data for the first soil layer on 3/1/2014 and no previous measurements. Since *M. sativa* grows in the same field as *A. nitens* and *C. lanata*, the ratios of how the parameters change with increasing soil depth for *A. nitens* and *C. lanata* were assumed to be the same as for *M. sativa*. The top 4 soil layers under *M. sativa* were sampled on 8/11/2012 and all 5 soil layers were sampled on 3/1/2013. The first soil layer for both of these dates was normalized to 1, and the subsequent layer parameters were divided by the value in the first layer to give a fractional relationship between the values of each parameter respective to the top soil layer. An example of this process is in Table 27.

Table 27: Example of procedure to find the relationship between soil layers for soil parameters. Data shown are for *Medicago sativa* on 3/1/2013. Soil layer depths are A (0-20cm), B (0-40cm), C (40-60cm), D (60-80cm), E (80-100cm).

parameter	units	Original values					% of A layer				
		A	B	C	D	E	A	B	C	D	E
pH		7.59	7.66	7.68	7.69	7.63	100%	101%	101%	101%	101%
EC	mS/cm	1.53	0.50	0.31	0.29	0.35	100%	33%	20%	19%	23%
HCO4	mg/eqv	0.46	0.44	0.43	0.47	0.45	100%	96%	93%	102%	98%
Cl	mg/eqv	1.73	0.74	0.38	0.44	0.33	100%	43%	22%	25%	19%
SO5	mg/eqv	6.31	1.27	0.68	0.70	1.08	100%	20%	11%	11%	17%
Ca	mg/eqv	4.57	0.85	0.60	0.60	1.00	100%	19%	13%	13%	22%
Mg	mg/eqv	1.21	0.55	0.18	0.33	0.30	100%	45%	14%	27%	25%
Na	mg/eqv	2.73	1.06	0.72	0.68	0.56	100%	39%	26%	25%	21%
K	mg/eqv	0.06	0.06	0.12	0.07	0.07	100%	100%	218%	118%	118%
TDS	%	0.63	0.17	0.10	0.10	0.12	100%	27%	16%	16%	20%
K2O	mg/kg	345.55	156.55	138.45	132.45	174.60	100%	45%	40%	38%	51%
P2O5	mg/kg	9.85	5.15	5.00	3.80	10.05	100%	52%	51%	39%	102%
N-NO3	mg/kg	6.10	4.15	4.40	4.15	3.25	100%	68%	72%	68%	53%

Parameter values for *A. nitens* and *C. lanata* in layers B, C, D, and E were assumed to have the same relationship between layers. Measured values for the top soil layer underneath *A. nitens* and, separately, *C. lanata*, were multiplied by the average interlayer relationship calculated for *M. sativa* to determine subsequent soil layer values for APEX. This process was done for every date that the top soil layer was measured (3/1/2013 and 6/28/2013 for *A. nitens* and 3/1/2013, 4/14/2013, and 8/4/2013 for *C. lanata*).

Salicornia europeae did not grow in the same location as *A. nitens*, *C. lanata*, and *M. sativa*, and therefore could not use this relationship. Measured values for all 5 soil layers were available for 8/11/2012 and 3/1/2013 underneath *S. europeae* in the solonchak. The values from 3/1/2013 were used as initial values in the APEX model. Soil layers B, C, D, and E were calculated for *S. europeaea* on 4/14/2013 and 6/28/2013 using the method described above, but with complete soil layer data for the solonchak on 8/11/2012 and 3/1/2013.

The same process was used at the Khorezm region to find layers B, C, D, and E on 6/15/2013. The % of first layer value was calculated using the dates 9/15/2012, 11/13/2012, and 3/1/2013, all of which had complete soil layer data. Soil data from 3/1/2013 were used as initial values for the Khorezm site.

3.2.4 Control File

The control file has 73 parameters. These parameters are used to control the APEX simulation such as specifying at what date to start the simulation, how many years to run the simulation, and what evapotranspiration equation to use. As with other tables, the control table has many parameters that are not essential to the model of Uzbek sites, and these parameters were set to default values. Only parameters that had been measured at the field sites were changed from default APEX settings. Appendix A contains all control table variables, values for both field sites, the accepted range for variables, and the reason for the baseline input value used for the Uzbek models. Major changes to the control file included specifying daily output, that climate data would be generated from monthly statistics, that the Penman-Monteith equation would be used for calculating evapotranspiration, and the salinity in the irrigation water measured by the PEER project. The simulation period was set as 3/1/2013 through 12/31/2013 on a daily time step.

3.2.5 Watershed File

A watershed must be created for each field site in APEX. Because of the flat terrain in Uzbekistan, a watershed is difficult to define, so instead a watershed was assumed to be the land on which the halophytes were grown. The watershed file itself includes 15 parameters including the watershed name, latitude and longitude, and elevation. Other parameters include peak runoff rate, and phosphorus and nitrogen uptake rates. All watershed parameters except latitude, longitude, elevation, weather station, and irrigation water salinity were left at default values. Appendix A includes a list of parameters and their definitions.

3.2.6 Subarea File

The subarea file is located within the watershed file. The watershed can be divided into several subareas that each can have their own crop rotations and management strategies. The subarea file has 107 parameters, but the majority are not essential for modeling the Uzbek sites and were set at default values of 0. Only 19 parameters in the subarea file were nonzero values. Of these 19 parameters, 5 are bookkeeping parameters meant to signify location, crop, soil, and weather generator to use.

The watershed for this project was divided into 4 subareas for each field site. Each subarea has a different crop (*C. lanata*, *A. nitens*, *S. europeae*, and *M. sativa*). The subareas were defined such that the *C. lanata* subarea was the extreme (uppermost) subarea, which drained to the *M. sativa* subarea, followed by the *A. nitens* subarea, and then the *S. europeae* subarea. Appendix A has a list of parameter definitions.

3.2.7 Management File

The management file is where irrigation, fertilizer, sowing, tilling, and harvesting schedules for simulations are defined. Management is described in table 28 for *A. nitens* and *C. lanata*. *S. europeae* had the same management as *A. nitens* and *C. lanata*, but without any irrigation or fertilizer since it was only measured growing wild in the solonchak. *M. sativa* also had the same management as *A. nitens* and *C. lanata*, but its management was set for 10 years since it is a perennial. Irrigation was set as furrow, gated pipe that is 75% efficient because it is the least efficient furrow irrigation method available in APEX (Table 28). The least efficient method was chosen because pipes are not used at the field sites in Uzbekistan. The fertilizer applied was custom made for the model to match the type of fertilizer used at Kyzylkezek: a N_{15}:P_6:K_6 blend. Crops were hand sown and hand harvested. Dates of fertilizer application were input based on data provided by the farmer at Kyzylkezek. The same fertilizer application dates were also used for the Khorezm site. Crops were irrigated in Uzbekistan based on when they reached different growth stages, so dates used in the model were best estimates by Dr. Kristina Toderich.

Table 28: Management table for *Atriplex nitens* and *Climacoptera lanata*. *Salicornia* europeae has the same management but lacks any type of irrigation or fertilizer. *Medicago sativa* has the same management, but the kill function occurs after the 10th year of growth.

Management	Operation	Date applied	Type applied	Rate
Irrigate	Irrigation, furrow, gated pipe, 75% efficiency	3/1/2013		86mm
Plant	Handsowing (custom)	3/22/2013		
Irrigate	Irrigation, furrow, gated pipe, 75% efficiency	4/1/2013		86mm
Fertilize		5/29/2013	N_{15}:P_6:K_6	80kg/ha
Irrigate	Irrigation, furrow, gated pipe, 75% efficiency	6/1/2013		86mm
Fertilize		7/15/2013	N_{15}:P_6:K_6	100kg/ha
Irrigate	Irrigation, furrow, gated pipe, 75% efficiency	9/1/2013		86mm
Harvest	Handharvest (custom)	9/10/2013		
Kill	Kill (stop growing plant permanently)	12/30/2013		

3.3 Sensitivity Analysis

Because many parameters had estimated values, a sensitivity analysis was done to determine what parameters to use for calibration. The sensitivity analysis was used to “weed out” non-sensitive parameters so that the calibration process could focus on appropriate values for sensitive parameters and be less time consuming. The sensitivity analysis consisted of 47 parameters: 19 in the soil data file, 6 in the soil list file, 17 in the crop file, 4 in the control file, and 1 in the subarea file (Appendix A). Soil data and soil list parameters were chosen to be included if they were necessary parameters (i.e., APEX required a value other than 0), or if they were assumed to be important to the salinity module. For example, ECND (EC of each soil layer) and CSLT (salinity of irrigation water) were included because they are salt input parameters for APEX. Both ECND and CSLT were measured at the field sites, but they were included in the sensitivity analysis because their relationship to crop growth and soil salinity are important for assessing salinity module performance. Allowable ranges for these parameters were taken from the APEX user manual (Steglich and Williams 2008; Appendix C). Control file parameters selected to be added to the sensitivity analysis were chosen due to lack of measured data, inability of APEX to generate the parameter, and probability of the parameter to affect the salinity module (e.g., CSLT). Allowable ranges for control file parameters were based on values given in the user manual (Appendix C). Crop parameters included in the sensitivity analysis were selected after consultation with Dr. Bob Nowak. Several additional crop parameters were included because they were changed in the initial crop parameterization. Allowable ranges for crop parameters in the sensitivity analysis were set to minimum and maximum parameter values used for all existing crops in the APEX database (Appendix C).

Base run parameter values are in Appendix A. The sensitivity analysis involved changing each parameter one at a time according to Eqn. 6:

$$Value\ Within\ Range\ at\ X\% = min + X\% * (max - min) \tag{6}$$

where min is the minimum value of the range, max is the maximum value of the range, and X% = 0, 25, 50, 75, or 100%.

Simulations were run through APEX for each parameter at each designated percentage value within the range for both the Khorezm and Kyzylkezek sites for a total of 468 runs (Appendix D). Model output for runs with different settings of sensitive parameters was compared to measured values for biomass, crop height, and EC for each soil layer. Graphs were made for each parameter for every respective metric, crop, and date versus the deviation between model output and measured results. Parameters that had the same deviation for all 5 values were considered insensitive and removed from the respective graph to provide a clearer picture of the influence of sensitive parameters.

3.4 Model Calibration and Assessment of Model Performance

Model calibration involved randomly varying sensitive parameter values to produce output that most closely matched measured values for the Uzbek sites. Instructions for calibration runs are in Appendix E. Only parameters found to be sensitive in the sensitivity analysis were included in calibration (Table 29). Graphs created for the sensitivity analysis (Appendix F) were used to find the range over which parameters were sensitive. Crop parameters were not changed in the calibration for *M. sativa* because parameter values already existed in the APEX database for the crop.

The same allowable ranges for parameters in the sensitivity analysis in Appendix C were used for calibration except for CBN, SAN, SIL, CPY, DLAP1, and RDMX (Table 30). Ranges for CBN, DLAP1, and RDMX parameters were changed to the sensitive region. Since soil texture of the Kyzylkezek site was observed to be primarily sand (Michael Rosen, personal communication), the allowable range for SAN for the Kyzylkezek model was changed to 50 to 90% and the allowable range for SIL was changed to 1 to 49%. The Khorezm site was observed to have a high clay content (Michael Rosen, personal communication), so the allowable range for SAN was changed to 1 to 40%, and SIL was allowed to range between 1 and 99%. The maximum value for CPY (fraction of phosphorous in yield in g/g) was changed from 12 to 0.05. The original CPY range was calculated by taking the maximum and minimum values of all previously existing crops in the APEX database. Upon further inspection, it was found that only two crops had a CPY value greater than 0.05. Since the units for CPY are g/g, the two crops with abnormally large CPY values were likely parameterized with incorrect units.

Table 29: Sensitive parameters and % of the range that each was sensitive. Blank cells indicate parameters that were not sensitive for that plant species.

Parameter	*Atriplex nitens*		*Climacoptera lanata*		*Salicornia europae*		*Medicago sativa*	
	Lower (%)	Upper (%)	Lower (%)	Upper (%)	Lower (%)	Upper (%)	Lower (%)	Upper (%)
BD	0	100	0	100	75	100	0	100
CBN	0	25	0	25	0	25	0	25
SAN	0	100	0	100	0	100	0	100
SIL				50	0	50	0	100
SALB	0	75	0	100			0	100
CPY			0	100	0	100		
DLAP1			0	75				
DLAP2			0	100				
DMLA			0	100				
GSI			0	100				
HMX			0	100				
RDMX			0	75				
WA			0	100				
WCY			0	100	0	100		

Table 30: New ranges for select sensitive parameters. All other sensitive parameter ranges remained as in Appendix A.

Parameter	Units	Kyzylkesek		Khorezm	
		Low	High	Low	High
CBN	%	1.0	25.5	1.0	25.5
SAN	%	50	90	1	40
SIL	%	1	49	1	99
CPY	g/g	0.0003	0.0500	0.0003	0.0500
DLAP1		1	49	1.00	75.25
RDMX	m	0.100	3.775	0.100	1.325

A trial and error method was used to calibrate the model. Random values for sensitive parameters were created, with a constraint that SAN and SIL parameters together could not exceed 99%.

R-squared error (Eqn. 7), % bias (Eqn. 8), and root mean squared error (RMSE; Eqn. 9) were the performance metrics used to compare model output for both the sensitivity analysis and calibration:

$$R^2 = \left(\frac{\sum_{t=1}^{n} (X_t^{obs} - \bar{X}^{obs}) * \left(X_t^{sim} - \bar{X}^{sim}\right)}{\sqrt{\sum_{t=1}^{n} (X_t^{obs} - \bar{X}^{obs})^2} * \sqrt{\sum_{t=1}^{n} (X_t^{sim} - \bar{X}^{sim})^2}} \right)^2 \qquad (7)$$

$$\% \, Bias = \frac{\sum_{t=1}^{n} (X_t^{sim} - X_t^{obs})}{\sum_{t=1}^{n} X_t^{obs}} \qquad (8)$$

$$RMSE = \sqrt{\frac{1}{n} * \sum_{t=1}^{n} \left(X_t^{sim} - X_t^{obs}\right)^2} \qquad (9)$$

where n is the number of observations, and X_t^{sim} and X_t^{obs} are simulated and observed values, respectively, of biomass, crop height, or soil EC values. The variable *t* indicates the date that observed and simulated values are tested against each other. $\bar{X}^{sim}$ and $\bar{X}^{obs}$ are respectively averages of simulated and observed biomass, crop height, or soil EC.

Some adjustments to model output were needed to calculate performance metrics. APEX outputs soil salinity as bulk salt, or WSLT, in units of kg/ha for each layer, but salinity information is input in terms of EC in mS/cm. APEX converts input EC measurements to WSLT with the following equation:

$$WSLT = \frac{6.4 * EC * ST}{FC} \qquad (10)$$

where WSLT is specific to a layer and a subarea, EC is electrical conductivity, ST is soil water content in mm, and FC is field capacity in percent. This relationship was used to convert the output WSLT back into EC so that observed and modeled EC could be compared for each layer. Additionally, APEX splits the number of soil layers from the input number of 5 (at 20 cm increments) into 10 at variable increments (Table 31). APEX outputs salinity in each of the 10 layers. To enable comparison of modeled and observed soil salinity, a weighted average by depth was taken for soil layers 1-3, 4-5, 6-7, and 8-9 to convert them back into the original 5 soil layers.

Graphs were made for each respective metric, location, crop, and date combination to compare deviations between observed and modeled parameter values as each changed throughout its range. Calibrated parameter values were those values for the run with the smallest RMSE. Parameter combinations that resulted in the smallest RMSE for biomass, EC, and crop height were also determined.

Table 31: Depth from the soil surface for the original parameterized 5 layers and the 10 APEX layers.

APEX layers	m below surface	Input layer	m below surface
1	0.01	A	0.2
2	0.11		
3	0.20		
4	0.30	B	0.4
5	0.40		
6	0.50	C	0.6
7	0.60		
8	0.70	D	0.8
9	0.80		
10	1.00	E	1.0

3.5 Data Used for Sensitivity and Calibration

Sensitivity analysis and calibration were performed by comparing model output with measured data from the two field sites. Data from Uzbekistan include observed biomass, crop height, and soil EC at the Kyzylkezek and Khorezm sites (Tables 32, 33, 34, and 35 respectively). Soil measurements for Khorezm are not specific to a plant because nothing grew at that location; all data for that location on each date come from 1 collected measurement. No biomass or crop height data were recorded for *S. europeae*, and no soil measurements were conducted for *M. sativa* past 3/1/2013. Because cultivated halophytes did not grow in Khorezm, biomass and crop height dates for Khorezm examined for model evaluation were the same as for the Kyzylkezek site and all measured values were 0 tonnes/ha or 0 m, respectively.

Table 32: Observed biomass at the Khorezm and Kyzylkezek sites in 2013 in tonnes/ha.

Plant	Date	Kyzylkesek	Khorezm
Climacoptera lanata	7/6/2013	14.53	0
C. lanata	10/12/2013	23.10	0
Atriplex nitens	7/6/2013	27.90	0
A. nitens	10/12/2013	42.05	0
Medicago sativa	7/6/2013	2.45	0

Table 33: Observed crop heights at the Khorezm and Kyzylkezek sites in 2013 in m.

Plant	Date	Kyzylkesek	Khorezm
Climacoptera. lanata	5/14/2013	0.17	0
C. lanata	6/17/2013	0.31	0
C. lanata	7/6/2013	0.39	0
C. lanata	10/12/2013	0.53	0
Atriplex nitens	5/14/2013	0.37	0
A. nitens	6/17/2013	1.36	0
A. nitens	7/6/2013	1.69	0
A. nitens	10/12/2013	2.05	0
Medicago sativa	5/14/2013	0.14	0
M. sativa	6/17/2013	0.20	0
M. sativa	7/6/2013	0.24	0

Table 34: Observed EC values at the Kyzylkezek site in soils under different crops.

Crop	Soil layer	Date	EC (mS/cm)
Climacoptera lanata	A	4/14/2013	2.32
C. lanata	B	4/14/2013	1.15
C. lanata	C	4/14/2013	1.20
C. lanata	D	4/14/2013	5.65
C. lanata	E	4/14/2013	0.53
C. lanata	A	8/4/2013	1.44
C. lanata	B	8/4/2013	0.71
C. lanata	C	8/4/2013	0.74
C. lanata	D	8/4/2013	3.50
C. lanata	E	8/4/2013	0.33
Atriplex nitens	A	6/28/2013	1.79
A. nitens	B	6/28/2013	0.89
A. nitens	C	6/28/2013	0.93
A. nitens	D	6/28/2013	4.36
A. nitens	E	6/28/2013	0.41
Salicornia europeae	A	4/14/2013	3.58
S. europeae	B	4/14/2013	2.36
S. europeae	C	4/14/2013	1.87
S. europeae	D	4/14/2013	1.94
S. europeae	E	4/14/2013	1.86
S. europeae	A	6/28/2013	7.12
S. europeae	B	6/28/2013	4.70
S. europeae	C	6/28/2013	3.72
S. europeae	D	6/28/2013	3.86
S. europeae	E	6/28/2013	3.69

Table 35: Observed EC values at the Khorezm site in 2013. "All crops" refers to *Atriplex nitens*, *Climacoptera lanata*, and *Salicornia europeae*.

Crop	Soil Layer	Date	EC (mS/cm)
All	A	6/15/2013	4.98
All	B	6/15/2013	1.67
All	C	6/15/2013	1.36
All	D	6/15/2013	1.17
All	E	6/15/2013	1.04

3.6 Management Scenarios

If the model is shown to adequately model salt dynamics for cultivated halophytes, management scenarios will be run with different combinations of irrigation and fertilizer input with the calibrated model to address research question 2. Irrigation options include flood, furrow, drip, and none. Fertilizer options include the N_{15}:P_6:K_6 blend currently being used at the field sites, goat manure, and no fertilizer.

4. Results

4.1 Sensitivity Analysis

The sensitivity analysis revealed which parameters affect model outcomes and therefore should be included in calibration (Tables 36 and 37). For example, Figures 17, 18, and 19 show how each parameter changes RMSE for biomass, crop height, and soil EC, respectively, at 0, 25, 50, 75, and 100% of each parameter's range for *A. nitens* on 7/6/2013. Although the sensitivity analysis just tested 5 values of each parameter, if a parameter showed no change in deviation for all 5 values, the parameter was assumed to be insensitive, and was not included in calibration runs. The majority of parameters did not change in deviation over their range. For example, fewer than 7 parameters had any deviation over their range for *A. nitens* in Khorezm (Figures 17, 18, and 19).

Sensitive parameters appeared sensitive over a portion or all of the range. For example, parameter CBN (soil organic carbon concentration) appeared to only be sensitive between 0 and 25% of its range for biomass, crop height, and soil EC below *A. nitens* in Khorezm on July 6, 2013 (Figures 17, 18, and 19). Graphs for each respective metric, location, crop, and date are in Appendix F. If a parameter appeared sensitive along a select portion of the range, then only that apparent sensitive range was allowed for calibration runs. Parameters that appeared to have the most effect on all crops, dates, and metrics were the soil parameters BD, SAN, SIL, CBN, and SALB. Crop parameters that appeared most sensitive were CPY and WCY (Table 36). Noticeably absent from the list of sensitive parameters was ECND (soil salinity in each layer). Parameter CSLT (irrigation water salinity) was not sensitive for biomass or crop height, and for soil EC it was only sensitive for 6 runs.

Table 36: Results from the sensitivity analysis. X's denote parameter was sensitive for the given metric, site, crop, and date. B= Biomass, CH = Crop Height. Kho = Khorezm, Kyz=Kyzylkezek, ATNI = *Atriplex nitens,* **CLLA=** *C. lanata,* **SAEU =** *Salicornia europeae.* **See Table 37 for parameter definitions.**

				Parameters															
Metric	**Site**	**Crop**	**Date**	**BD**	**SAN**	**SIL**	**CBN**	**SALB**	**CPY**	**DLAP1**	**DLAP2**	**DMLA**	**GSI**	**HMX**	**RDMX**	**WA**	**WAVP**	**WCY**	**CSLT**
B	Kho	*ATNI*	7/6	X	X	X	X	X	X									X	
B	Kho	*ATNI*	10/12	X	X	X	X	X	X									X	
CH	Kho	*ATNI*	5/14	X	X	X	X	X	X									X	
CH	Kho	*ATNI*	6/17	X	X	X	X	X	X									X	
CH	Kho	*ATNI*	7/6	X	X	X	X	X	X									X	
CH	Kho	*ATNI*	10/12	X	X	X	X	X	X									X	
EC	Kho	*ATNI*	6/15	X	X		X	X	X									X	
B	Kho	alfalfa	7/6	X	X		X	X	X									X	
CH	Kho	alfalfa	5/14	X	X	X			X				X					X	
CH	Kho	alfalfa	6/17	X	X	X													
CH	Kho	alfalfa	7/6	X	X	X													
B	Kho	*CLLA*	7/6	X	X	X	X	X	X	X	X	X	X		X	X	X	X	
B	Kho	*CLLA*	10/12	X	X	X	X	X	X	X	X	X	X		X	X	X	X	
CH	Kho	*CLLA*	5/14		X	X	X	X	X	X	X		X	X	X			X	
CH	Kho	*CLLA*	6/17		X	X	X	X	X	X	X		X	X	X			X	
CH	Kho	*CLLA*	7/6		X	X	X	X	X	X	X		X	X	X			X	
CH	Kho	*CLLA*	10/12		X	X	X	X	X	X	X		X	X	X			X	
EC	Kho	*CLLA*	6/15	X	X		X	X	X									X	X
EC	Kho	*SAEU*	6/15	X	X		X	X	X									X	
B	Kyz	*ATNI*	7/6																
B	Kyz	*ATNI*	10/12																
CH	Kyz	*ATNI*	5/14																
CH	Kyz	*ATNI*	6/17																
CH	Kyz	*ATNI*	7/6																
CH	Kyz	*ATNI*	10/12																
EC	Kyz	*ATNI*	6/28	X	X		X	X											X
B	Kyz	alfalfa	7/6	X	X	X	X	X	X				X						
CH	Kyz	alfalfa	5/14	X	X	X	X	X	X										
CH	Kyz	alfalfa	6/17	X	X	X													
CH	Kyz	alfalfa	7/6	X	X	X													
B	Kyz	*CLLA*	7/6	X	X	X	X	X	X	X	X	X	X		X	X			
B	Kyz	*CLLA*	10/12	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
CH	Kyz	*CLLA*	5/14		X	X	X	X	X	X	X		X	X	X			X	
CH	Kyz	*CLLA*	6/17		X	X	X	X	X	X	X		X	X	X			X	
CH	Kyz	*CLLA*	7/6		X	X	X	X	X	X	X		X	X	X			X	
CH	Kyz	*CLLA*	10/12		X	X	X	X	X	X	X		X	X	X			X	
EC	Kyz	*CLLA*	4/14	X		X	X	X	X									X	X
EC	Kyz	*CLLA*	8/4	X	X	X	X	X	X										X
EC	Kyz	*SAEU*	4/14	X	X	X	X	X	X									X	
EC	Kyz	*SAEU*	6/28	X	X	X	X												
# sensitive				26	33	29	29	28	28	12	12	4	14	9	12	4	3	24	4

Table 37: Definitions of sensitive parameters

Parameter	Definition
BD	Moist bulk density
SAN	Sand content
SIL	Silt content
CBN	Organic carbon concentration
SALB	Soil albedo
CPY	Fraction of phosphorus in crop yield
WCY	Fraction of water in crop yield
DMLA	Maximum potential leaf area index
DLAP1	First point on optimal leaf area development curve
DLAP2	Second point on optimal leaf area development curve
RDMX	Maximum root depth
WA	Biomass-energy ratio
GSI	Maximum stomatal conductance
WAVP	Parameter relating vapor pressure deficit to WA

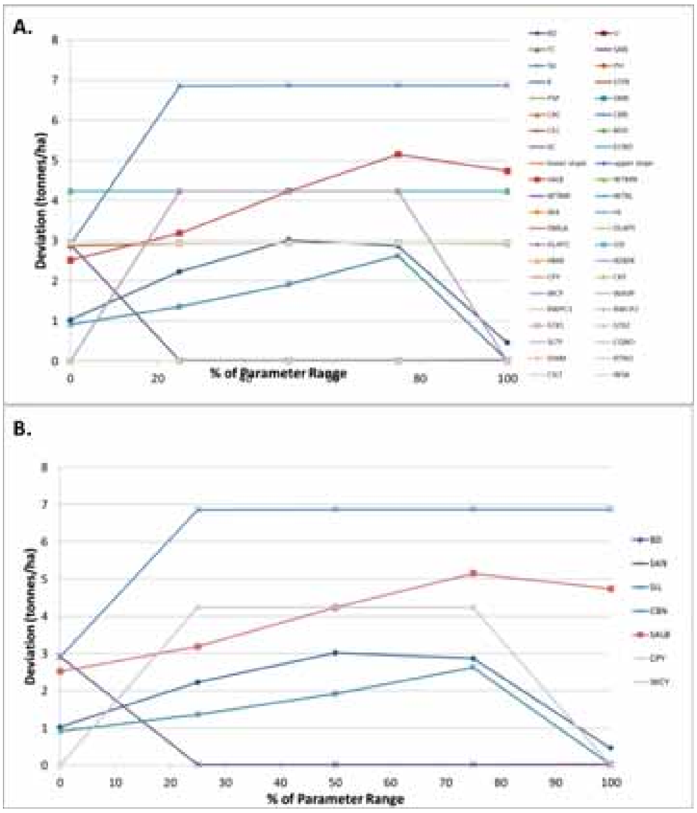


Figure 17: Sensitivity of A) all parameters and B) only sensitive parameters for biomass of *Atriplex nitens* in Khorezm on 7/6/13. Positive deviation indicates model simulated more biomass than was observed

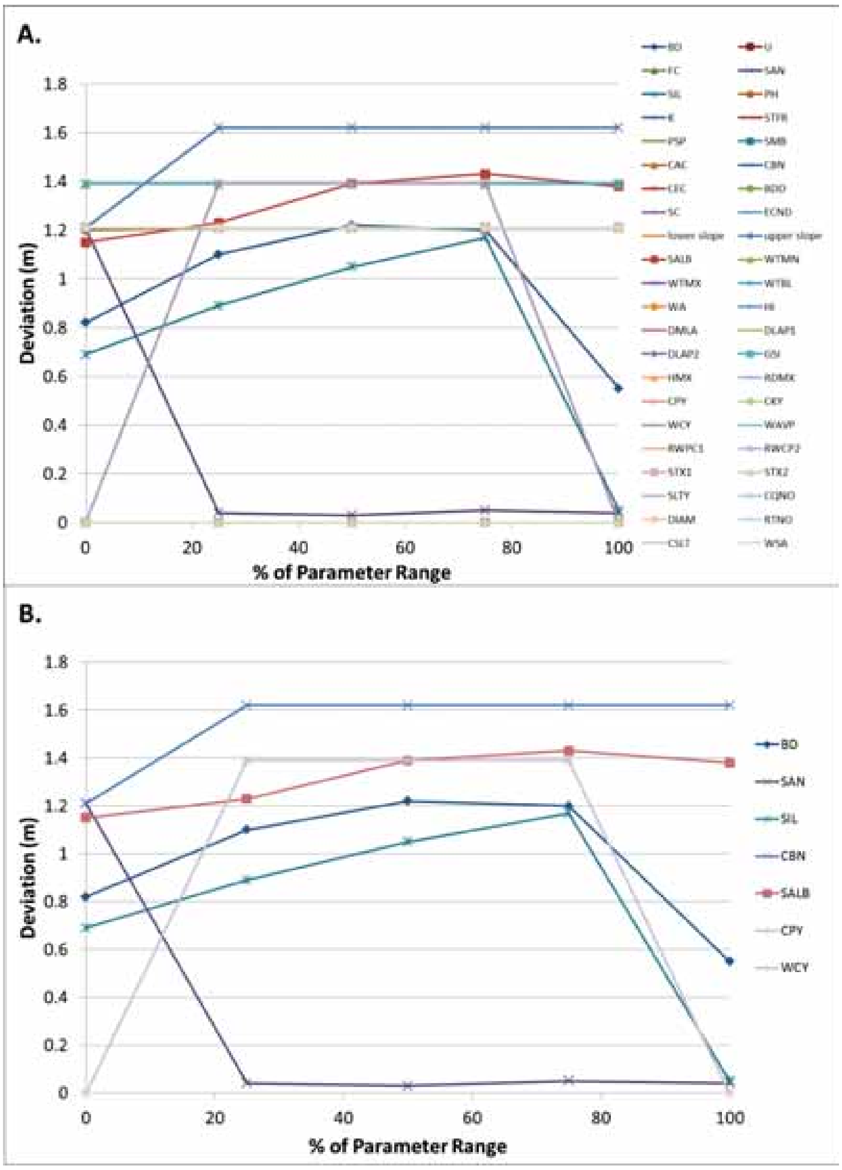


Figure 18: Sensitivity of A) all parameters and B) only sensitive parameters for crop height of *Atriplex nitens* in Khorezm on 7/6/13. Positive deviation indicates model simulated more biomass than was observed.

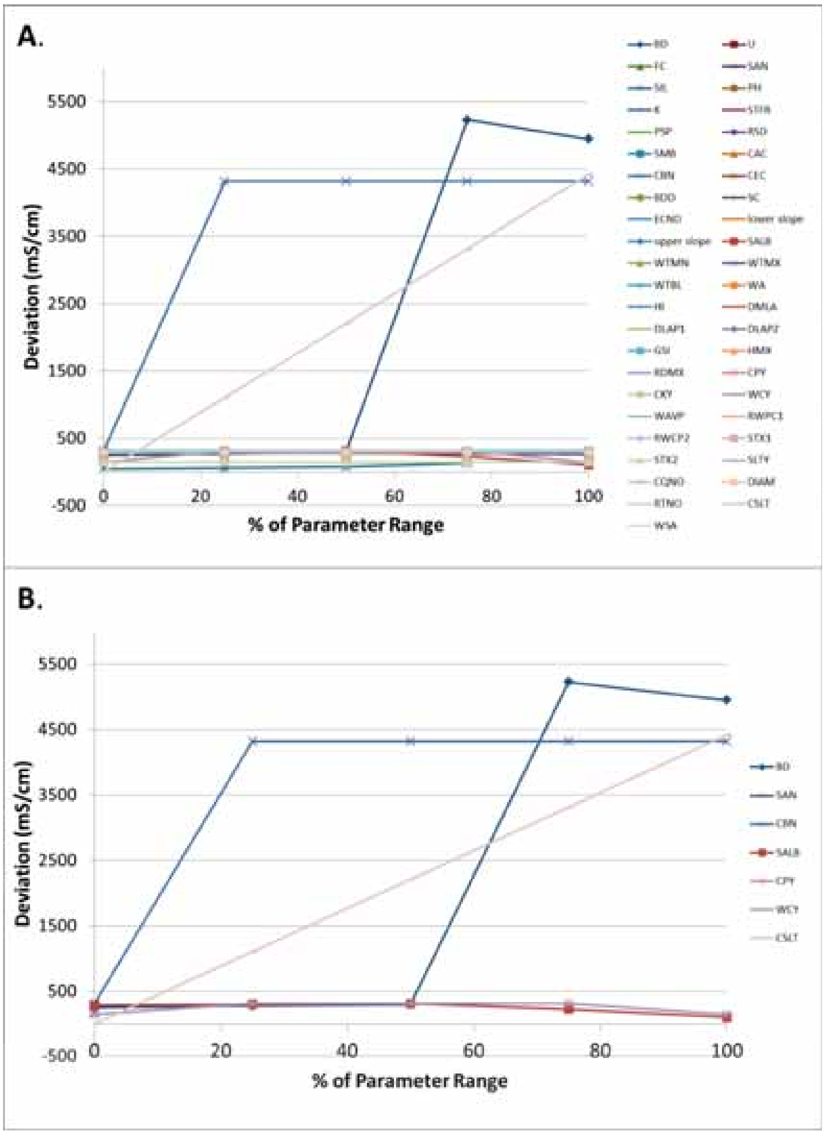


Figure 19: Sensitivity of A) all parameters and B) only sensitive parameters for soil EC for *Atriplex nitens* in Khorezm on 6/15/13. Positive deviation indicates model simulated more biomass than was observed.

APEX was unable to model *A. nitens* growing at the Kyzylkezek site. No parameters were sensitive for either the biomass or crop height metrics (Figure 20). Only soil parameters and CSLT (irrigation water salinity) were sensitive for soil EC metric for *A. nitens* at Kyzylkezek.

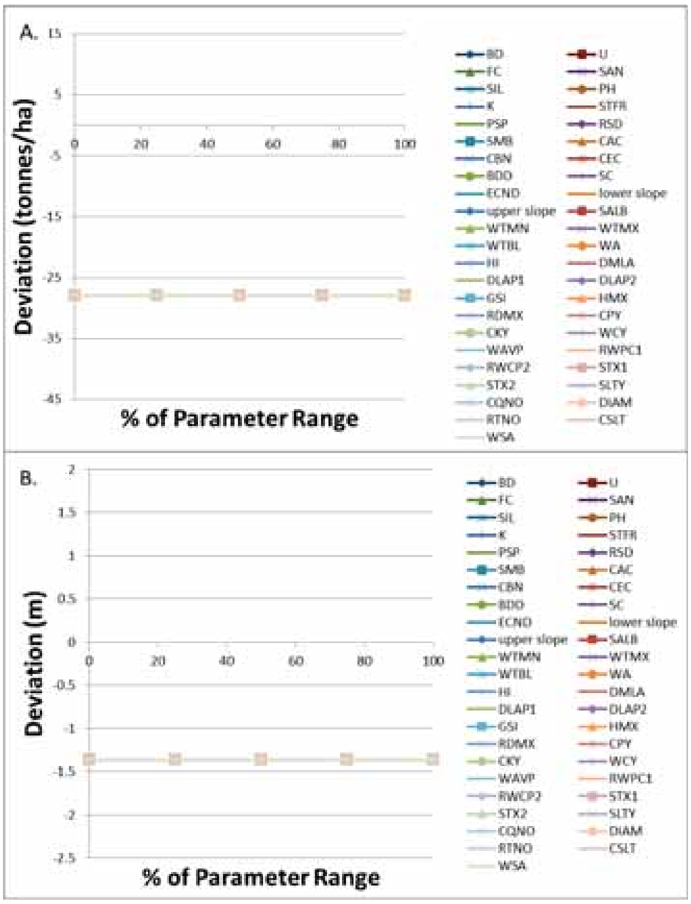


Figure 20: Sensitivity of parameters for *Atriplex nitens* in Kyzylkezek for A) 7/6 biomass B) 6/17 crop height. All other dates showed similar relationships.

4.2 Calibration

Overall, the model was unable to be calibrated. Model parameter values for the run with the lowest overall RMSE of the 500 runs for the Khorezm and Kyzylkezek models were chosen as the "best fit" parameters for analysis of model performance. In addition, parameter values for model runs with the lowest RMSE for each individual metric (biomass, soil EC, and crop height) were noted (Tables 38, 39, 40, and 41).

RMSE for soil EC dominated when calculating average RMSE of all metrics: the range for biomass RMSE was 0.25 to 50 kg/tonne for biomass, 7.11 to 5950 mS/cm for soil EC RMSE, and 0.25 to 1.46 for crop height RMSE in Khorezm, and similar ranges were seen in Kyzylkezek. Only soil parameters were changed for *M. sativa* because the crop was previously parameterized into the APEX database (Table 40).

Table 38: RMSE, r^2 and % bias results for each model fit for Kyzylkezek.

	RMSE	r^2	% bias	N
Overall best fit	10.26	0.26	-0.58	-
Best fit biomass (tonnes/ha)	23.02	0.07	-0.53	5
Best fit soil EC (mS/cm)	4.01	0.00	-0.29	11
Best fit crop height (cm)	0.98	0.20	-0.77	5

Table 39: RMSE, r^2 and % bias results for each model fit for Khorezm. Blank spaces indicate that statistic was unable to be calculated because observed crop height and biomass were 0 tonnes/ha and 0 m respectively.

	RMSE	r^2	% bias	N
Overall best fit	4.50	-	-	-
Best fit biomass (tonnes/ha)	0.35	-	-	5
Best fit soil EC (mS/cm)	7.11	0.27	1.55	11
Best fit crop height (cm)	0.25	-	-	3

Table 40: Best fit parameter values for Kyzylkezek site. Columns indicate lowest overall RMSE and lowest RMSE for biomass, soil EC, and crop height. ATNI = *Atriplex nitens*, **CLLA =** *Climacoptera lanata*, **SAEU =** *Salicornia europeae*, **MSAT =** *Medicago sativa*

Crop	Parameter	Units	Parameter value			
			Overall best fit	Best fit biomass	Best fit soil EC	Best fit crop height
ATNI	**BD**	**g/cm^3**	1.29	1.21	1.29	2.34
	CBN	**%**	5.32	17.08	5.32	5.29
	SAN	**%**	60.67	52.01	60.67	54.05
	SIL	**%**	27.74	33.14	27.74	13.21
	SALB	**-**	0.73	0.06	0.73	0.03
CLLA	**BD**	**g/cm^3**	1.47	1.30	1.47	1.25
	CBN	**%**	4.19	4.15	4.19	2.68
	SAN	**%**	62.40	56.82	62.40	44.79
	SIL	**%**	19.98	32.07	19.98	45.62
	SALB	**-**	0.81	0.35	0.81	0.43
	CPY	**g/g**	0.02	0.04	0.02	0.00
	DLAP1	**-**	50.21	38.70	50.21	27.90
	DLAP2	**-**	71.26	35.88	71.26	20.50
	DMLA	**-**	19.39	9.26	19.39	18.38
	GSI	ms^{-1}	0.00	0.04	0.00	0.04
	HMX	**m**	2.54	3.84	2.54	0.28
	RDMX	**m**	0.21	0.41	0.21	2.16
	WA	**-**	23.18	61.57	23.18	22.12
	WCY	**-**	0.40	0.89	0.40	0.89
SAEU	**BD**	**g/cm^3**	2.06	2.21	2.06	2.19
	CBN	**%**	3.22	10.73	3.22	22.85
	SAN	**%**	53.99	51.25	53.99	51.21
	SIL	**%**	34.22	16.77	34.22	36.93
	CPY	**g/g**	0.02	0.05	0.02	0.01
	WCY	**-**	0.83	0.13	0.83	0.29
MSAT	**BD**	**g/cm^3**	1.57	0.67	1.57	2.13
	CBN	**%**	9.20	24.04	9.20	13.11
	SAN	**%**	50.80	60.03	50.80	56.70
	SIL	**%**	24.73	23.26	24.73	23.01
	SALB	**-**	0.07	0.17	0.07	0.83

Table 41: Best fit parameter values for Khorezm site. Columns indicate lowest overall RMSE and lowest RMSE for biomass, soil EC, and crop height. ATNI = *Atriplex nitens*, CLLA = *Climacoptera lanata*, SAEU = *Salicornia europeae*.

Crop	Parameter	Units	Parameter value			
			Overall best fit	Best fit biomass	Best fit soil EC	Best fit crop height
All	BD	g/cm^3	0.98	2.47	1.25	2.44
	CBN	%	1.94	15.59	3.61	18.27
	SAN	%	15.93	23.86	24.25	26.09
	SIL	%	26.20	62.54	23.80	44.39
	SALB	-	0.99	0.13	0.98	0.07
ATNI	CPY	g/g	0.03	0.04	0.02	0.03
	WCY	-	0.52	0.30	0.90	0.09
CLLA	CPY	g/g	2.06	2.21	2.06	2.19
	DLAP1	-	3.22	10.73	3.22	22.85
	DLAP2	-	53.99	51.25	53.99	51.21
	DMLA	-	34.22	16.77	34.22	36.93
	GSI	ms^{-1}	0.02	0.05	0.02	0.01
	HMX	m	2.44	0.55	0.48	3.62
	RDMX	m	0.15	0.78	0.14	1.31
	WA	-	90.60	38.89	58.62	2.68
	WAVP	-	11.66	2.84	9.83	14.60
	WCY	-	0.06	0.58	0.02	0.81
SAEU	CPY	g/g	0.01	0.02	0.02	0.04
	WCY	-	0.01	0.02	0.02	0.04

Plots were made to visually depict the difference between observed and modeled values for each of the best fit models (Appendix G). Modeled versus observed graphs show the model vastly over predicted soil salinity for *C. lanata* and *A. nitens*, but maintained crop growth at both the Khorezm and Kyzylkezek sites, even though in reality, no crops grew in Khorezm (Figures 21 and 22 respectively).

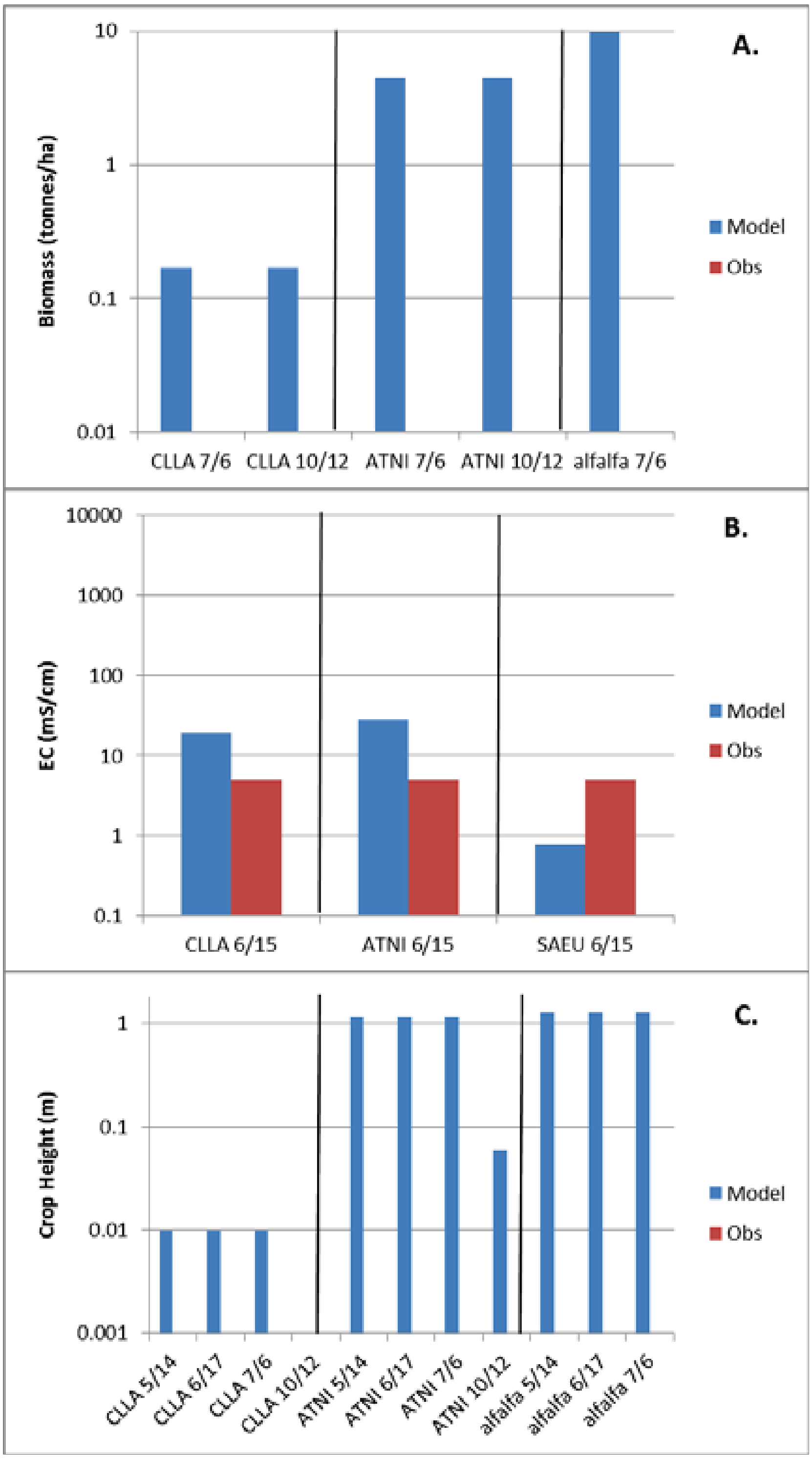


Figure 21: Best fit model results for Kyzylkezek region. Observed versus modeled results for A) biomass, B) EC, and C) crop height. CLLA = *Climacoptera lanata*, **ATNI =** *A. nitens*, **SAEU =** *Salicornia europeae*.

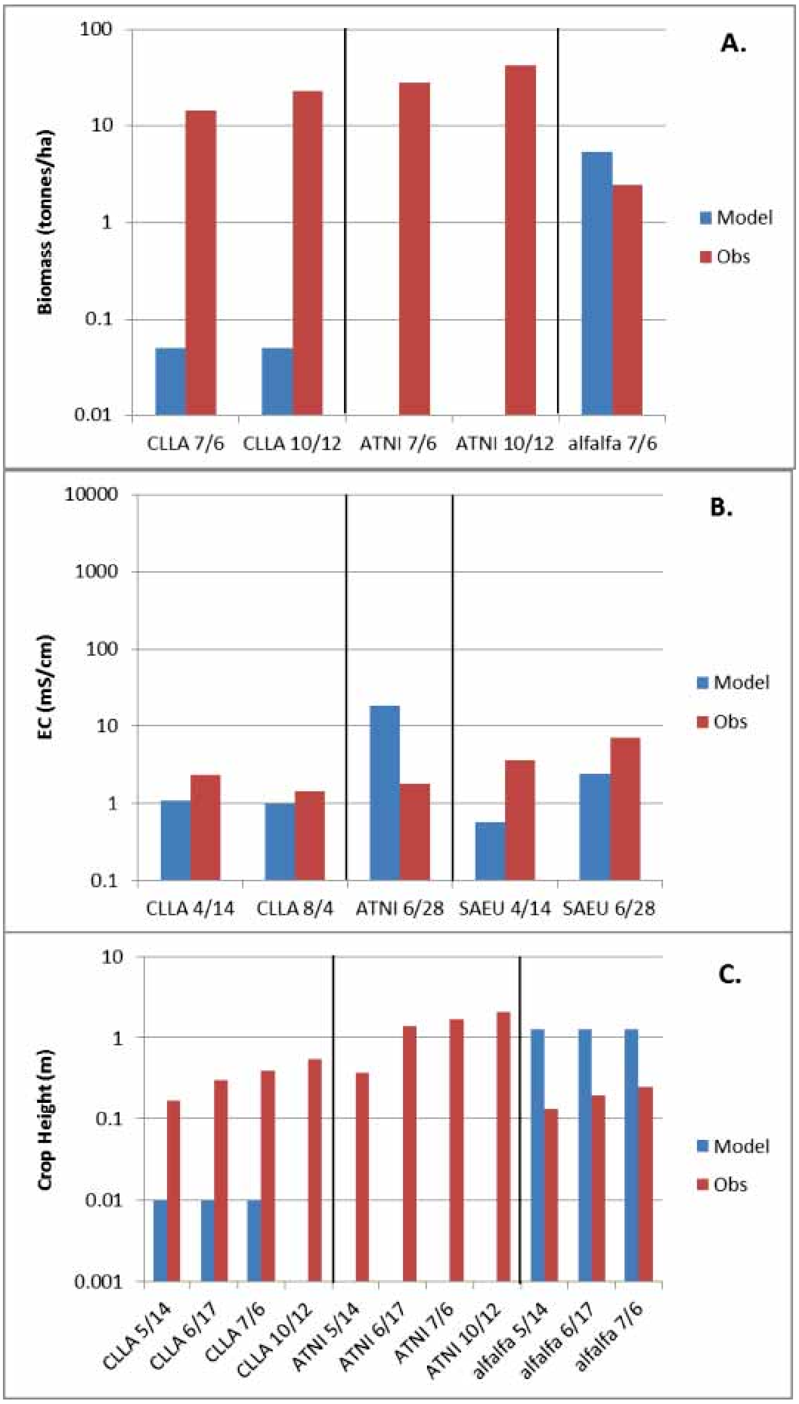


Figure 22: Best fit model results for Khorezm region. Observed versus modeled results for A) biomass, B) EC, and C) crop height. CLLA = *Climacoptera lanata*, **ATNI =** *Atriplex nitens*, **SAEU =** *Salicornia europeae*.

Dotty plots were created to visually show parameter values versus RMSE for the 500 runs for each field site and crop (Appendix H). These plots differ from sensitivity analysis plots because other parameter values were also varying. Dotty plots can be useful for showing when a particular parameter has more dominant sensitivity over other parameters (Beven 2012; Wagener and Kollat 2006). This analysis was not done for r^2 and % bias because calculations of these metrics had too few observation points.

For most parameters, dotty plots did not indicate much sensitivity in reducing RMSE. Some higher values of BD (bulk density) appear to result in smaller crop height RMSE for all crops at Khorezm (Figure 23). Additionally, higher values of SALB (soil albedo) appeared to increase RMSE for biomass and crop height, but not for soil EC (Figure 24). All modeled soil EC for soil layer A was greater than observed values. All sites and parameters showed two bands of soil EC RMSE throughout the parameter range. For Kyzylkesek, these soil EC RMSE values were about 760 to 800 and 5 to 30 mS/cm, and for Khorezm they were 1900 to 1930 and 10 to 100 mS/cm for Khorezm. More scatter was observed in the dotty plots for Khorezm than for Kyzylkezek.

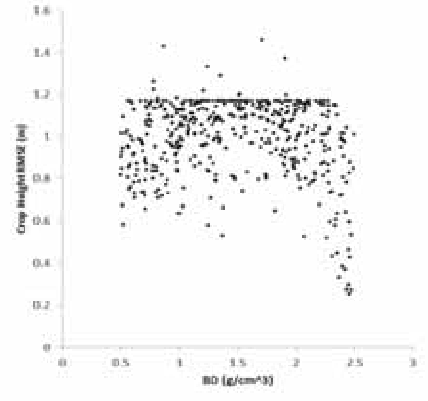


Figure 23: Crop height RMSE versus BD values for all crops at Khorezm site.

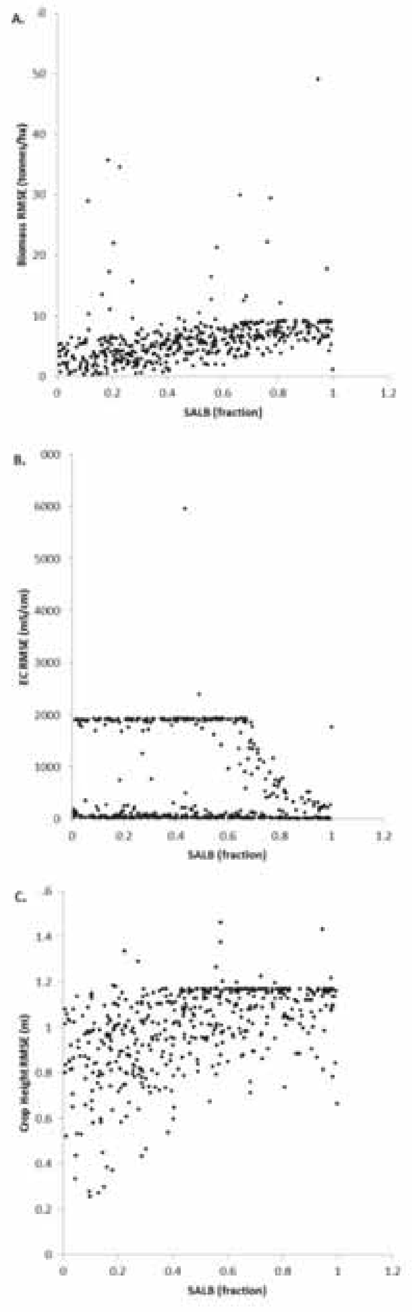


Figure 24: RMSE versus SALB values for A) biomass, B) soil EC, and C) crop height for all crops at Khorezm. Because no crops actually grew in Khorezm, actual biomass and crop height were 0 tonnes/ha and 0 m, respectively.

4.3 Management Scenarios

Management scenarios were not run because the model was unable to be calibrated.

5. Discussion

5.1 Sensitivity Analysis

The sensitivity analysis showed that some saline parameters that were expected to be sensitive when applying a salinity module were not sensitive. For example, ECND (soil salinity) was not sensitive, so an increase in soil salinity did not have an effect on modeled crop height or biomass (Figure 25). ECND also had little effect on soil EC, indicating the parameter is not being used by the model, or soil salinity may be dominated by salt in irrigation water. Additionally, CSLT (irrigation water salinity) was not sensitive for most metrics, crops, and dates, even at very large salt concentrations of 50 g/L (Figure 26).

This lack of sensitivity means that salt stress is not appropriately represented in APEX and the model does not appear to have a threshold of salinity that would kill crops or stop them from germinating. Salt stress in crops is a real problem that should be represented by the model. The greenhouse experiments conducted by Dr. Nowak and Ms. Johnson indicated that *A. nitens* cannot survive at irrigation water salinities of as little as 3 mS/cm. Balnokin et al. (2005) found that *S. europeae* and *C. lanata* had decreased yields at soil salinity of less than 450 mmol Na^+/dm^3 and 300 Na^+/dm^3, respectively. Although a good relationship for conversion of Na^+/dm^3 to units of mS/cm does not exist, the Balnokin et al. (2005) study demonstrates that the modeled halophytes do have thresholds of salinity tolerance, and this relationship is not currently represented in APEX.

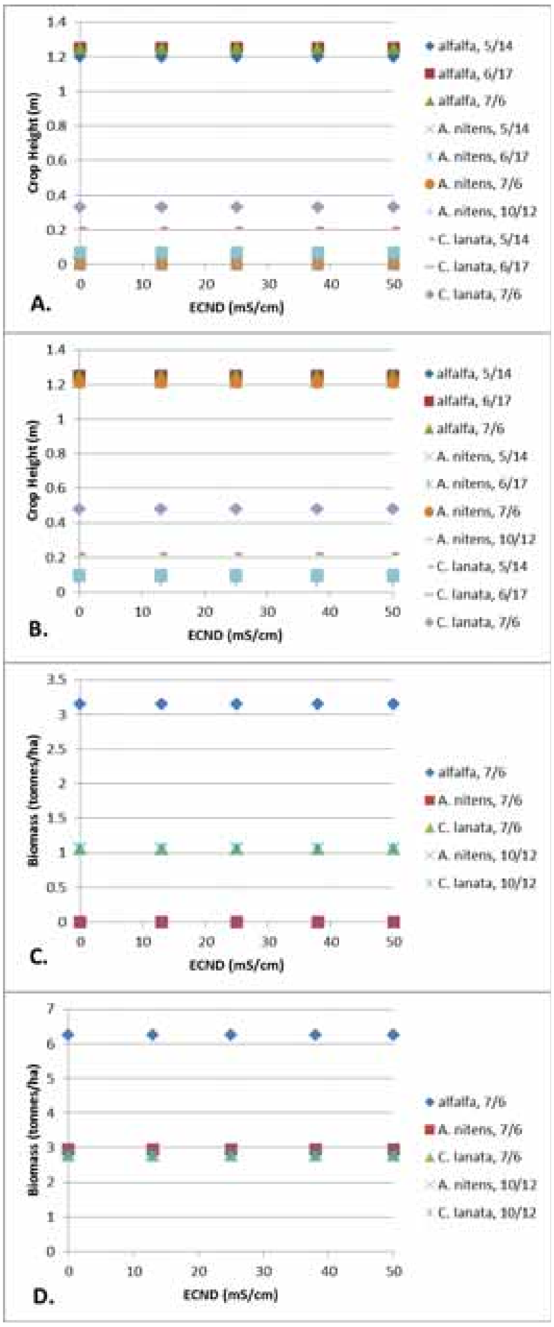


Figure 25: Effect of the parameter ECND (soil EC) on A) modeled crop height in Kyzylkezek, B) crop height in Khorezm, C) plant biomass in Kyzylkezek, and D) crop biomass in Khorezm.

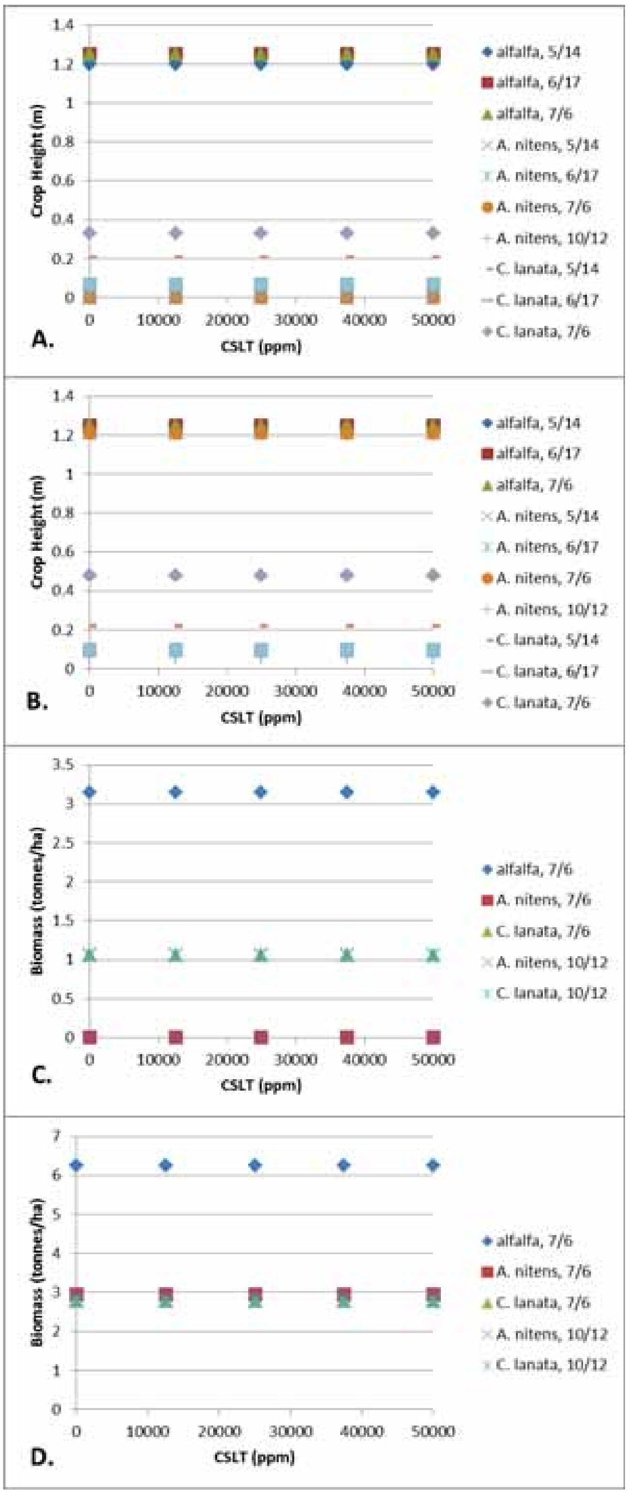


Figure 26: Effect of the parameter CSLT (soil EC) on A) modeled crop height in Kyzylkezek, B) crop height in Khorezm, C) plant biomass in Kyzylkezek, and D) crop biomass in Khorezm.

5.2 Calibration and Model Performance

The model was able to run for the parameterized field sites, crops, and management scenario. However, the model was unable to be calibrated after 500 runs with random parameter values. It is possible that more runs or a more refined sensitivity analysis would yield better results, but in the time frame of this project only an initial assessment of model performance was possible. Model results for the best fit runs demonstrated consistent failure of the model to represent field conditions. Three possible reasons why the model did not calibrate are improper parameterization due to incorrect assumptions, inadequate data for model input, and coding issues.

Because of the vast number of parameters in the APEX model, many parameters were left at default values. In the interest of time, not all unknown parameters were included in the sensitivity analysis. Parameters were included in the sensitivity analysis based on intuition and recommendations from experienced scientists regarding what would likely be important to the model. An obvious flaw was that all model runs showed all crops growing in Khorezm where no crops grew in reality, and *A. nitens* did not grow at Kyzylkezek in model runs even though it did grow well at the field site. None of the model parameters were sensitive to *A. nitens* in Kyzylkezek, and we were unable to find a combination of model parameters that would enable *A. nitens* to grow even though it would grow in Khorezm runs. Not finding sensitive parameters for *A. nitens* at Kyzylkezek may indicate that important sensitive parameters for crop growth were improperly parameterized and not included in the sensitivity analysis. Due to the number of parameters, it is likely that accidentally dismissing sensitive parameters may have been a problem for more than just *A. nitens* at the Kyzylkezek site. For example, leaving the peak runoff rate at the default value of 1 (normal range is 0.5 to 1.5) may be an incorrect assumption; there is little runoff, so a more appropriate value for the peak runoff rate may have been closer to 0.

Crop parameters especially may have been improperly parameterized. The majority of crop parameter values came from assuming that each respective halophyte was similar to previously parameterized crops by visual observation. Key parameters were then changed also by visual observation. Changing parameters based on photographs was the only option for most of the parameters, so having improper parameter values is extremely likely. Several other parameters were changed based on values found in literature. Although literature values are better than estimations via visual observation, the values in the literature could have been measured for a different strain of the halophyte that has slightly different characteristics than those grown in Uzbekistan. Field or lab experiments with the modeled plants could improve crop parameter estimation.

Additionally, the watershed setup may have influenced model results. The model was set up for both sites so that water from *C. lanata* flowed to *M. sativa* then *A. nitens* and then to *S. europeae*. The actual flow of water may have been different, especially since these 3 halophytes were not the only three crops being grown and studied. In reality, *S. europeae* was not growing in the same field with the same water as *C. lanata* and *A.*

nitens. If *S. europeae* is continued to be monitored in the solonchak, future iterations of this project should distinguish a separate watershed in APEX for *S. europeae*.

Inadequate field data may also have been a factor in the poor model performance. Soil layers were parameterized for all horizons despite only having data for soil layer A on the date closest to planting. Interpolated values for soil layers B, C, D, and E for nitrogen content, phosphorus content, potassium content, pH, and soil EC may have been incorrect and affected crop growth, crop biomass, and soil EC. Field data from Uzbekistan lacked several other important site characteristic values such as sand and silt content and bulk density. Additionally, weather for each site was generated from monthly statistics that were calculated with only 7 years of discontinuous weather data. Seven years of weather data was probably inadequate for calculating descriptive weather statistics. Ideally the model would run with daily weather data collected from the field site during the same time period as was modeled to reduce error caused by simulating improper weather. Crop growth is sensitive to daily minimum and maximum temperatures, so correct weather data would minimize error. Furthermore, dates of crop irrigation were estimated since actual crop irrigation dates were not recorded.

Multiple issues also existed with the salinity module, including with salt percolating downwards through the soil profile for irrigated crops. The salt concentration and EC in soil layers A and B was unrealistically high for crops that were watered with saline water (i.e., *M. sativa*, *A. nitens*, *C. lanata*). For example, the modeled EC in soil layer A in Kyzylkezek for *A. nitens* on 6/28 was about 3800 mS/cm, which is higher than the irrigation water salinity of about 3.81 mS/cm. *S. europeae* did not exhibit high salt values in top soil layers, perhaps because it was not irrigated with saline water (Figure 27). APEX underestimated soil EC in most soil layers for *S. europeae*.

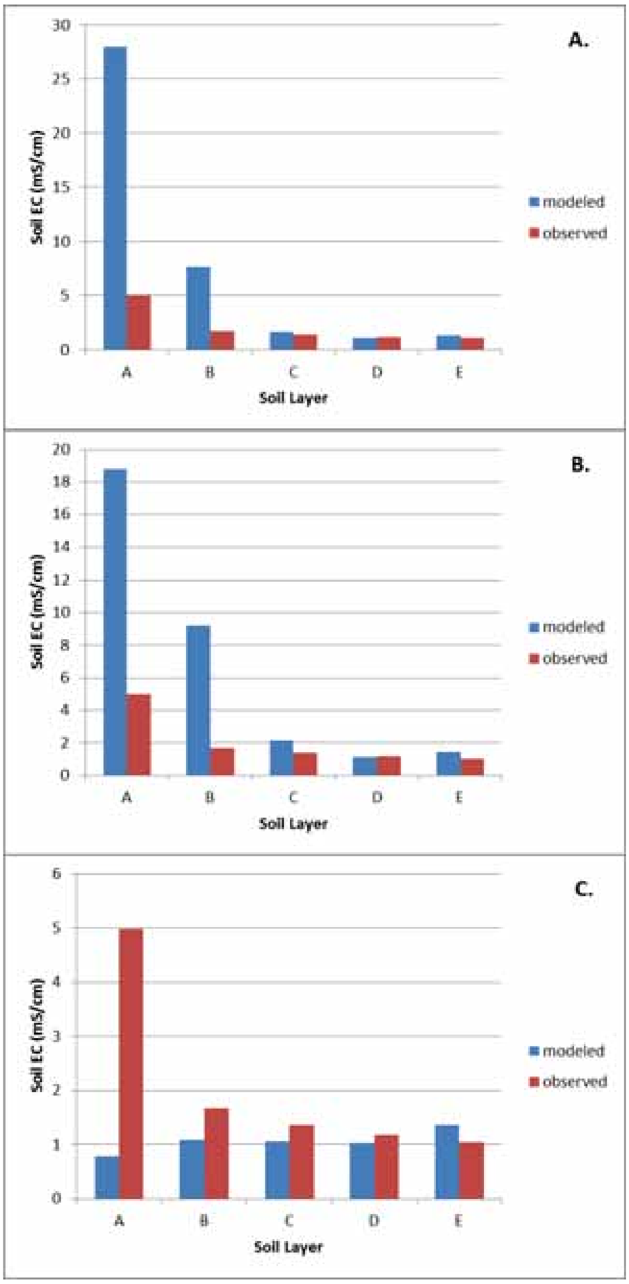


Figure 27: Modeled versus observed soil layer EC for the best fit model for A) *Atriplex nitens*, **B)** *Climacoptera lanata*, **and C)** *Salicornia europeae* **for Khorezm site.**

The dotty plots revealed an interesting phenomenon about soil EC RMSE: many of the 500 runs resulted values of soil EC within two separate ranges for each site model (Figure 28). For Kyzylkesek, these soil EC RMSE values were about 760 to 800 and 10 to 30 mS/cm, and for Khorezm they were 1900 to 1930 and 10 to 100 mS/cm. The soil EC RMSE bands correspond to actual soil EC values that were as high as 140 mS/cm. A mass balance calculated with known soil EC and irrigation water salinity and amount for the field sites show that the maximum average EC in soil layer A (0-20cm) would be 3.1, 1.6 and 1.6 mS/cm after irrigation for the Khorezm, Kyzylkezek *A. nitens*, and Kyzylkezek *C.lanata* sites respectively. The mass balance assumed a 1:1 soil to water ratio, no water drainage, and no percolation below the 1st soil layer. All of these assumptions were made to calculate the greatest likely soil EC at each of the sites and to show that the modeled EC values are unrealistically high. All modeled soil EC values were greater than observed values. The higher values for Khorezm as compared to Kyzylkezek could be related to higher irrigation water salinity (3310 versus 2437 ppm) or the less sandy soil (16% sand for Khorezm versus 61% for Kyzylkesek). Based on the rule of thumb that 1 mS/cm = 640 ppm, both sets of parallel lines have a higher EC than the irrigation water, which could indicate that salt was concentrating in soil layers after evapotranspiration.

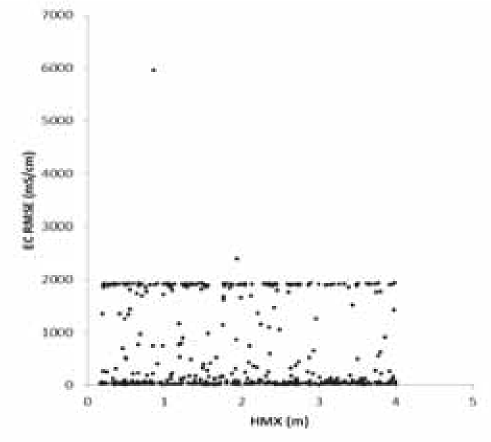


Figure 28: Dotty plot for HMX and EC RMSE in the Khorezm site.

Only BD (bulk density) and SALB (soil albedo) had any apparent influence on soil EC RMSE for the Khorezm site (Figure 29). This phenomenon was not observed for Kyzylkezek EC RMSE for any parameters. Higher soil albedo means that the soil is more reflective. Theoretically, an increase in soil albedo should cause increased reflectivity and therefore decrease surface evaporation (USDA 1996). Decreased evaporation would result in higher soil water content and less concentrated salt content, which was not the effect simulated by the model

In regards to BD, larger bulk densities result in decreased hydraulic conductivities (Dianqing et al. 2004), so for higher BD, salt would not percolate as well, resulting in higher soil EC. For the APEX model, larger EC RMSE occurs only at higher values of BD. The model overestimated soil EC for all runs. However, the magnitude of the difference between measured and observed soil EC is unrealistically large, and the BD and SALB relationships to EC RMSE were not observed for any crops at Kyzylkezek.

Thus, it seems possible that errors in the modeling process or input data are causing these apparent sensitivities.

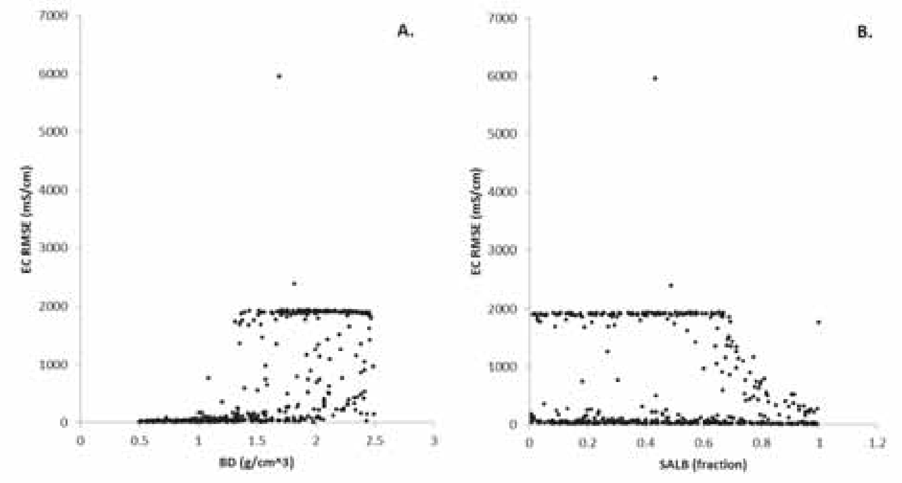


Figure 29: Dotty plot for A) BD and B) SALB at the Khorezm site (all crops).

Conducting the sensitivity analysis and calibration manually was not time efficient and left the results open to human error. Future iterations of this project should use a program that can test multiple variables at a time and find the sensitivity and calibrate at the same time. The Model-Independent Parameter Estimation and Uncertainty Analysis (PEST) tool may be an efficient way to assess future model performance. PEST can adjust model parameter data to minimize the difference between the model-generated numbers and corresponding measurements. The model inputs are the adjustable parameters and the real-world observations. PEST is able to rewrite the model input files using parameters that are appropriate for the optimization process and calculate the difference between the model output and measured data. PEST uses the calculated difference to adjust the model input and run the model again (US Environmental Protection Agency 2014).

5.3 Suggested Model Improvements

The APEX salinity module is a step in the right direction to create simulations of salt movement through the soil-plant-water interface. The next step would be to determine whether the salinity module of EC could be improved. For example, the accumulation of salt in top soil layers should be addressed, and toxicity of salinity to plants should be incorporated. Future iterations of model development should include differentiating salt ions due to differing impacts of certain ions on plant physiology. The balance of Ca^{2+} and Na^{+} should especially be modeled because high uptake of Na^{+} and low uptake of Ca^{2+} by plants in sodic soils affects membrane permeability and reduces the transport of other nutrient ions. Low Ca^{2+} concentrations can also cause increased uptake of toxic elements such as Zn, Ni, Mg, Pb, Se, Al, and B (Naidu and Rengasamy 1993). Differentiating ions is also important because different EC values can come from the same mass of salt depending on the weight of the ions in the soil water. A more complete synopsis of how sodic soils affect agriculture is in Appendix I.

Ultimately, a model that includes different salt management strategies for halophytes to deal with the salts (i.e., ion excretion, ion avoidance, and succulence) would be useful for determining the best crops to improve soil quality. The current APEX salinity module is coded for succulent halophytes because a fraction of plant biomass is salt. Most halophytes germinate best under fresh water conditions or salinities less than 0.1 NaCl, so salt movement to the top soil layer is especially important to be modeled (Khan and Gul 2008). Salt movement to the top soil layer could occur by plants or evaporation moving salt from lower to upper soil layers, or it could also occur when halophytes excrete salts out of their biomass and back onto the top soil layer. Representation of all halophyte survival mechanisms, including ion avoidance, would allow plants to raise salt from deeper soil layers. Raising salt to upper soil layers could concentrate the salt at higher levels, making plant germination more difficult. Model representation of ion excretion halophytes should allow them to take up salt into their biomass, but enable a precipitation or high wind event to remove a portion of that salt back to the soil surface.

Currently, the APEX salinity module is mainly based on the assumption that halophytes need a certain amount of salt and will uptake salt that will compose a certain percent of plant biomass. Since salt can also have detrimental effects on conventional crops and halophytes, the model should have the capability of showing crops dying or failing to germinate under certain soil or irrigation water salinities. A simple relationship between relative crop yield as a function of soil EC may be able to represent this dynamic (Wu, personal communication; Figure 30). The crop would yield 100% of its potential up until a certain threshold value of EC. At this threshold value ($EC_{threshold}$), the relative yield of the crop would decrease linearly until the crop would not yield anything ($EC_{extinction}$). These thresholds would be different for each crop and relatively greater for the halophytes (Wu personal communication).

A couple of changes to how parameters are specified in the salinity module are also recommended. The soil table includes parameter ECND (EC in mS/cm for each soil layer), but this parameter must be rounded to the nearest whole number. Allowing more significant figures will enable input of measured values more precisely.

In addition, APEX currently parameterizes irrigation water salinity (CSLT) in the control file, restricting irrigation water salinity to a constant value for the duration of the model run. However, irrigation water salinity may change over time, or crops may be irrigated with different water sources of different salinities, as was done in the field tests of the Khorezm site: the first irrigation came from highly saline groundwater and subsequent irrigations came from less saline lake water. Allowing the model to simulate such conditions should improve model performance.

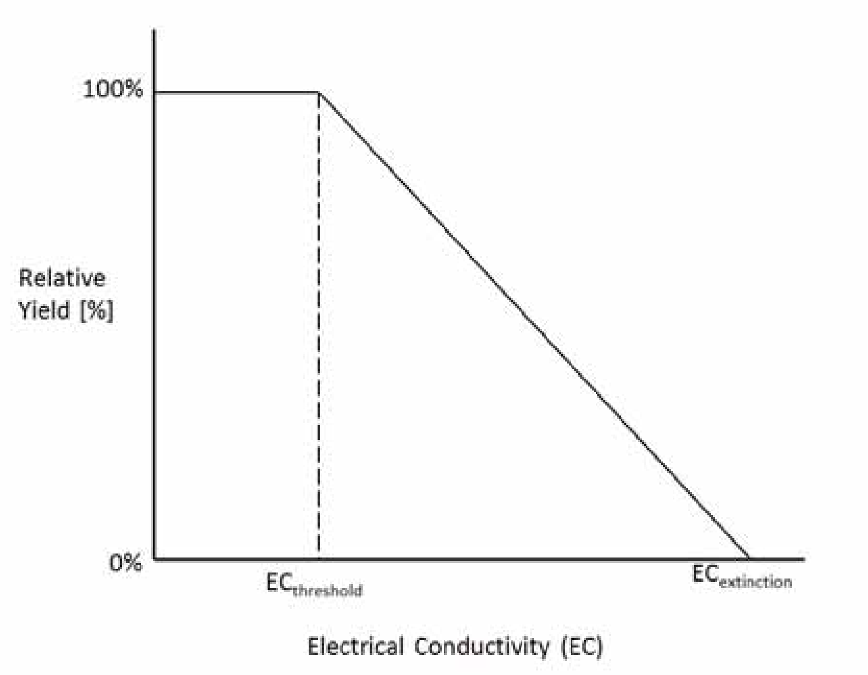


Figure 30: Relative yield as a function of soil EC (Wu personal communication).

5.4 Field Recommendations

The sensitivity analysis revealed parameters that currently appear to affect model results, indicating that these parameters are especially important to measure in the field to enable the model to be parameterized with appropriate values. The most important soil parameters to be measured are sand and silt content, albedo, organic carbon concentration, and bulk density. Most of these parameters would only need to be measured once per season and are common measurements. Based on the sensitivity analysis, the most important crop parameters to measure are the fraction of phosphorus in the yield and the fraction of water in the yield at the time of harvest.

Future models should use better weather data. If weather is to be generated, several decades of weather data would be better than 7 years to calculate the monthly statistics. However, measured daily weather (i.e., daily solar radiation, minimum and maximum air temperatures, precipitation, relative humidity, and wind speed) for the time period that was modeled is preferred over generated weather. Improperly simulated weather could have affected the model outcome. For example, temperature (hot or cold) or water (wet or dry) stress could have affected plant growth in reality at the field sites, but may not have been simulated because generated, rather than actual, weather was used.

Further iterations of this project will benefit from additional data taken at more frequent intervals. Soil layers A, B, C, D, and E below each crop should be sampled during each plant sampling. Soil and plant sampling should occur as often as possible. Monthly testing would result in more data points to compare modeled versus observed values. Additional metrics to supplement crop height, biomass, and soil EC could be added with additional crop data, such as plant salt content. Additional watershed data should be recorded, such as which crop is watered first and the order in which each subsequent crop is watered. Actual irrigation dates should also be recorded.

5.5 Research Questions Addressed

The two research questions that were planned to be addressed by this research were:

Question 1: Can planted and harvested halophytes remove or maintain soil salts?
Question 2: What management strategies (fertilizer, irrigation, etc.) are most effective for removing soil salts?

Neither of these questions can be adequately answered because of poor model results. Once a calibrated model is obtained in future iterations of this project, these questions can be properly addressed by the model. The way APEX models outtake of soil salts by having a percentage of the crop biomass be salt suggests that harvested halophytes may be able to remove or maintain soil salts, although future iterations of halophyte modeling will also have to show reduced halophyte and glycophyte yields due to salt stress.

6. Conclusions

This project has been a first step towards a larger project to assess the potential for halophytes to remediate land that is negatively affected by soil salinity. The larger project will parameterize more halophytes and assess the potential for halophytes to serve as an economic resource as well as a means for phytoremediation.

The APEX salinity module needs further refinement to adequately model halophytic plants and their effect on soil, water, and crop production. A more advanced model that is capable of modeling negative impacts of salinity on crops is essential not only to show how halophytes respond to saline conditions, but also how conventional crops fare. Ultimately, it will be useful to have a model that can simulate responses of plants to different anions and cations because different ions have different impacts on crops. Future efforts should also include coordinated field data collection to enable more effective model testing.

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Appendix A: APEX Parameters

This appendix includes every parameter in APEX along with their units, definition, and initial values for the base run for sensitivity analysis and before calibration.

Table 42: Crop file parameters, definitions, and initial values for *Atriplex nitens*, *Climacoptera lanata*, and *Salicornia europeae*. Italics indicate parameter included in the sensitivity analysis. Bold indicates sensitive parameter.

	units	*Atriplex nitens*	*Climacoptera lanata*	*Salicornia europeae*	definition
CPNM		30.00	90.00	16.00	crop name
WA		*0.99*	*0.99*	*0.99*	*Biomass-energy ratio / Radiation Use Efficiency*
HI		*24.00*	*35.00*	*10.00*	*Harvest Index*
TG	C	4.00	10.00	30.00	Optimal Temp
TB	C	3.00	1.50	4.50	Min temp for plant growth
DMLA		*0.95*	*1.00*	*0.99*	*Max potential leaf area index*
DLAI	%	10.05	25.23	20.20	Fraction of growing season when leaf area declines
DLAPI		*90.95*	*40.86*	*99.99*	*First point on optimal leaf area development curve*
DLAP2		*0.10*	*0.10*	*0.01*	*second point on optimal leaf area development curve*
RLAD		0.10	0.10	0.01	Leaf area index decline rate parameter
RBMD		3.00	3.00	5.00	Biomass-energy ratio decline rate parameter
ALT		0.01	0.01	0.01	Aluminum tolerance index
GSI	*ms-1*	*0.85*	*0.85*	*0.85*	*Maximum stomatal conductance*
CAF		35.00	35.00	80.00	critical aeration factor
SDW	kg/ha	1.85	0.16	0.76	seeding rate
HMX	*m*	*0.50*	*1.00*	*1.00*	*Maximum crop height*
RDMX	*m*	*660.41*	*661.22*	*660.15*	*maximum root depth*
WAC2		0.05	0.06	0.00	CO2 Concentration / Resulting WA value (Split Variable)
CNY	g/g	0.01	0.01	0.00	Fraction of nitrogen in yield
CPY	*g/g*	*0.06*	*0.02*	*0.02*	*Fraction of phosphorus in yield*

CKY		*0.95*	*0.80*	*0.80*	*Fraction of potassium in yield*
WYSF	0 to HI	0.60	0.60	0.95	Lower limit of harvest index
PST		35.84	5.60	10.11	Pest factor
COSD	$	120.00	120.00	1.00	Seed cost
PRY1	$/kg	5.00	5.00	1.00	price for yield
PRY2	$/t	0.53	0.92	0.76	price for forage yield
WCY		*0.07*	*0.07*	*0.01*	*Fraction water in yield*
BN1		0.04	0.06	0.00	Nitrogen uptake parameter (N fraction in plant at emergence)
BN2		0.03	0.06	0.00	Nitrogen uptake parameter (N fraction in plant at maturity)
BN3		0.01	0.01	0.00	Nitrogen uptake parameter (N fraction in plant at maturity)
BP1		0.00	0.00	0.00	Phosphorus uptake parameter (P fraction in plant at emergence)
BP2		0.00	0.00	0.00	Phosphorus uptake parameter (P fraction in plant at 0.5 maturity)
BP3		0.07	0.04	0.02	Phosphorus uptake parameter (P fraction in plant at maturity)
BK1		0.07	0.04	0.02	Potassium uptake parameter (P fraction in plant at emergence)
BK2		0.07	0.03	0.02	Potassium uptake parameter (P fraction in plant at 0.5 maturity)
BK3		1.27	1.27	3.39	Potassium uptake parameter (P fraction in plant at maturity)
BW1		0.63	0.63	3.39	Wind erosion factor for standing live biomass
BW2		0.73	0.73	3.90	Wind erosion factor for standing dead biomass
BW3		5.00	5.00	5.00	Wind erosion factor for flat residue
IDC		5.01	5.01	5.00	Crop category number
FRST1		15.95	15.95	15.00	First point on frost damage curve
FRST2		5.00	5.00	6 to 8	Second point on frost damage curve
WAVP		*1.00*	*1.00*	*1.00*	*Parm relating vapor pressure deficit (VPD) to WA*
VPTH		4.75	4.75	3.50	Threshold VPD (KPA)
VPD2		0.40	0.40	0.40	VPD value (KPA)
RWPC1		0.13	0.20	0.20	Fraction of root weight of emergence
RWPC2		100.00	100.00	100.00	Fraction of root weight at maturity
GMHU		10.20	20.20	10.20	Heat units required for germination

PPLP1		50.90	100.90	50.90	Plant population for crops and grass-1st point on curve
PPLP2		0.12	0.12	0.12	Plant population for crops and grass-2nd point on curve
STX1		*1.70*	*1.70*	*1.70*	*Salinity effect on yield*
STX2		*0.01*	*0.01*	*0.01*	*Salinity threshold*
BLG1		0.10	0.10	0.10	Lignin fraction in plant at 0.5 maturity
BLG2		0.00	0.00	0.00	Lignin fraction in plant at full maturity
WUB		0.00	0.00	0.00	Water use conversion to biomass
SLTY		0.10	0.10	0.10	Fraction of salt in yield

Table 43: Control file parameters, definitions, acceptable range according to the APEX User Manual, and initial values for the Khorezm and Kyzylkezek sites. Italics indicate parameters included in the sensitivity analysis. Bold indicates sensitive parameter.

Parameter	units	range	Khorezm	Kyzylkezek	definition
NBYR	years	1 to 100	1	40	Years of simulation duration
IYRO		1 to 2040	2013	1960	beginning year
IMO		1 to 12	1	1	beginning month
IDA		1 to 31	1	1	beginning day
IPD		0 to 9	4	4	print code
NGN		from -1 to 2345	0	0	weather input code
IGN		0 to 100	0	0	number of random number cycles
LPYR		0 or 1	0	0	leap year considered
IET		0 to 5	1	1	potential ET equation
ISCN		0 or 1	0	0	Stochastic CN estimator code
ITWP		from -1 to 4	0	0	Peak rate estimate code
ISTA		0 or 1	0	0	Soil profile code
IHUS		0 or 1	0	0	Automatic Heat Unit scheduling
NVCNO		0 to 4	4	4	Variable daily CN or non-varying CN
INFLO		0 to 4	0	0	Runoff Q estimation methodology
MSNP		0 or 1	0	0	Nutrient/Pesticide output file
IERT		0 or 1	0	0	Enrichment Ratio method for EPIF or CLEAMS
LBP		0 or 1	0	0	Soluble Phosphorus runoff estimate
NUPC		0 or 1	0	0	N and P plant uptake

					concentration code
MNUL		0 to 3	0	0	Manure application code
LPD		0 to 365	0	0	Lagoon pumping
MSCP		0 to 365	0	0	Solid manure scraping
ISLF		0 or 1	0	0	Slope length/steepness factor
NAQ		0 or 1	0	0	Air Quality Analysis
IHV		0 to 2	0	0	0 for no flood routing, 1 for flood routing
ICO2		0 to 2	0	0	Atmospheric CO2
ISW		0 to 5	0	0	soil water calculation code
RCNO	ppm	0.5 to 1.5	0.8	0.8	Average concentration of nitrogen in rainfall
CO20	ppm	50 to 10000	330	330	CO2 concentration in atm
CQNO	*ppm*	*1 to 10000*	*0*	*0*	*Conc of N in irrigation water*
PSTX		0 to 10	1	1	Pest damage scaling factor
YWI		0 to 20	10	10	number years of max monthly 0.5 hr rainfall record
BTA		0 to 1	0	0	coeff used to est wet-dry prob given mon wet days
EXPK		0 to 2	0	0	parameter used to modify exp rain distribution
QG	mm/hr	1 to 100	25	25	channel capacity flow rate
QCF		0.4 to 0.6	0.5	0.5	exponent in watershed area flow rate EQ
CHSO	m/m	0.001 to 0.7	0.5	0.5	average upland slope in watershed
BWD	m/m	1 to 20	5	5	channel bottom width/depth
FCW	m/m	2 to 50	10	10	floodplain width/channel width
FPSC	mm/hr	1 to 5	1	1	floodplain saturated hydraulic conductivity
GWSO	mm	5 to 200	50	50	max ground water storage
RFTO		0 to 365	0	0	ground water residence time in days
RFPO	mm	0 to 1	0.5	0.5	return flow / (return flow+deep percolation)
SATO	km	0.01 to 10	1	1	Saturated Conductivity adjustment factor
FL	km	0.001 to 12	2	2	Wind run length

FW	km	0.001 to 12	1	1	wind run width
ANGO		0 to 360	0	0	clockwise angle of field length from North
UXP		0.1 to 0.5	0.3	0.3	Power parameter of modified exp dist of wind speed
DIAM	*µm*	*100 to 500*	*500*	*500*	*soil particle diameter*
ACW		0 to 10	1	1	wind erosion control factor
GZLO	t/ha	0 to 5	0	0	above ground plant material grazing limit
RTNO		*0 to 10000*	*0*	*0*	*number of years of cultivation at start of simulation*
BXCT		0 to 1	0	0	linear coefficient of change in rainfall from E to W
BYCT		0 to 1	0	0	linear coefficient of change in rainfall from S to N
DTHY		0.05 to 12	1	1	time interval for flood routing
QTH	mm	0 to 200000	5	5	Routing Threshold
STND	mm	0 to 200000	5	5	VSC routing used when reach storage
DRV		0 to 7	3	3	equation for water erosion
PCOO		0 to 1	0	0	Fraction of subareas controlled by ponds
RCCO		0 to 0.5	0.2	0.2	reach channel C Factor
CSLT	*ppm*	*0 to 100000*	*3310.615*	*2437.253631*	*Salt concentration in irrigation water*
IGMX		0 to 500	0	0	Number of times generator seeds are initialized
IMWO	days	0 to 360	0	0	min interval between auto mowing
IOX		0 to 1	0	0	oxygen/depth function switch
IDNT		0 to 1	0	0	denitrification subprogram switch
IAZM		0 to 1	0	0	Azimuth orientation switch
IPAT		0 to 1	0	0	Auto Phosphorus swith
IHRD		0 to 2	0	0	GRAZING MODE
IWTB		5 to 30	15	15	Duration of antecedent period for rainfall

Table 44: Subarea file parameters, definitions, and acceptable ranges according to the APEX User Manual. Initial subarea values are located in Table 44. Italics indicate parameters included in the sensitivity analysis. Bold indicates sensitive parameter was sensitive.

	units	range	definition
CNUM			CNUM = County Name
INPS			INPS = Soil number; soil from soil list
IOPS			IOPS = Operation schedule
LCNO			LCNO = LCNO (Land Condition)
IOW			IOW = Owner ID; must be entered
II		0 to 10	Feeding area herd number
IAPL			IAPL = Auto. Manure Feed Lot ID
NVCN		0 to 4	NVCN = Soil Moisture Index
WITH			WITH = Daily Weather Station
SNO	mm		SNO = Water content of snow (MM)
STDO	t/ha		STDO = Standing dead crop residue (t/ha)
LONG			LONG = X Coordinate of subarea centroid
LAT			LAT = Y Coordinate of subarea centroid
AZM		0 to 360	AZM = Azimuth orientation of land slope
WSA	*ha*	*0.1 to 5*	*WSA = Size of Subarea(ha)*
CHL	km		CHL = Distance From Outlet to Most Distant Point in Subarea
CHD	m		CHD = Channel depth(m) , in (m)
CHS	m/m		CHS = Mainstream channel slope(m/m)
CHN			CHN = Channel roughness factor
STP	m/m		STP = Average Upland Slope (m/m)
SPLG	m		SPLG = Ave Upland Slope Length (m)
UPN			UPN = The surface roughness Mannings N in Upland.
FFPQ			FFPQ = Fraction of buffer/floodplain flow
RCHL	km		RCHL = Length of Routing Reach

RCHD	m		RCHD = Channel Depth of Routing Reach
RCBW	m		RCBW = Bottom Width of Channel of Routing Reach
RCTW	m		RCTW = Top Width of Channel of Routing Reach
RCHS	m/m		RCHS = Channel Slope of Routing Reach
RCHN			RCHN = Channel Mannings N of Routing Reach
RCHC			RCHC = USLE Crop Management Channel Factor
RCHK		0.0001 to 0.5	RCHK = USLE Erodibility Channel factor.
RFPW	m		RFPW = Buffer/Floodplain width
RFPL	km		RFPL = Buffer/Floodplain length
RSEE	m		RSEE = Elevation at emergency spillway elevation
RSAE	ha		RSAE = Total reservoir surface area at emergency spillway elevation
RSVE	mm		RSVE = Runoff volume at emergency spillway elevation
RSEP	m		RSEP = Elevation at principal spillway elevation
RSAP	ha		RSAP = Total reservoir surface area at principle spillway elevation
RSVO	mm		RSV0 = Volume at principal spillway elevation
RSV	mm		RSV = Initial reservoir volumes
RSYS	ppm		RSYS = Initial sediment concentration in reservoirs
RSYN	ppm		RSYN = Normal sediment concentration in reservoirs
RSHC	mm/hr		RSHC = Hydraulic conductivity of reservoir bottoms
RSDP			RSDP = Time required for the sediment to return to the normal
RSBD	t/M^3		RSBD = Bulk Density of Sediment in Reservoir
ISAO			ISAO = 0 = For Normal OR Subarea ID receiving outflow
NIRR			NIRR = Rigidity of irrigation code
IRR			IRR = Irrigation Code
IRI			IRI = Minimum Application Interval for automatic irrigation
IFA	days		IFA = Minimum fertilizer application interval
LM		0 to 1	LM = Liming Code

IFD		0 to 10	IFD = Furrow Dike Code
IDR	mm		IDR = Drainage code
IDF1			IDF1 = Liquid Fertilizer Number
IDF2			IDF2 = Solid Manure From Feeding Area Stock Pile
IDF3			IDF3 = Automatic commercial fertilizer application for P
IDF4			IDF4 = Automatic commercial application
IDF5			IDF5 = Automatic solid manure application
BIR			BIR = Irrigation Auto Trigger
EFI			EFI = Runoff Irrigation
VIMX	mm		VIMX = Maximum annual irrigation volume
ARMN	mm		ARMN = Minimum single application volume
ARMX	mm		ARMX = Maximum single application volume
BFT			BFT = Auto Fert. Trigger
FNP4	kg		FNP4 = Auto Fert. Application Rate (N)
FMX	kg/ha		FMX = Maximum annual N fertilizer applied for a crop
DRT	days		DRT = Time requirement for drainage system to end plant stress
FDSF			FDSF = Fraction of furrow dike volume available for water storage
PEC			PEC = Erosion Control Practice Factor
DALG			DALG = Fraction of Feed Lot Subarea controlled by lagoon.
VLGN			VLGN = Normal Lagoon Volume/Maximum (fraction)
COWW			COWW = Lagoon input from wash water
DDLG			DDLG = Time to reduce lagoon storage from maximum to normal in day
SOLQ			SOLQ = Ratio Liquid/Total manure applied in this Feed Lot Subarea
SFLG			SFLG = Safety factor for Lagoon spillover
FNP2	kg/ha		FNP2 = Feeding Area Stock Pile Auto Solid Manure Appl. Rate
FNP5	kg/ha		FNP5 = Automatic Manure application rate
IMW	days		IMW = Min. interval between Automatic mowing(days)
URBF		0 to 10	URBF = Fraction of Subarea which is Urban
PCOF			PCOF = Fraction of Subarea that is Controlled by ponds
BCOF		0 to 10	BCOF = Fraction of the Subarea controlled by Buffers
BFFL	m		BFFL = Buffer Flow Length
FIRG		0.8 to 1.5	FIRG = Adjustment factor for the volume of auto irrigation the model will apply in relation to field capacity.

FL			FL = WIND RUN LENGTH
FW			FW = WIND RUN WIDTH
ANGL			ANGL = CLOCKWISE ANGLE OF FIELD LENGTH FROM NORTH
NY (1)			NY = Select herd(s) eligible for grazing this crop
XTP (1)			XTP = Select herd(s) eligible for grazing this crop

Table 45: Initial subarea values for the Khorezm and Kyzylkezek sites. Definitions, units, and acceptable ranges according to APEX User manual are in Table 43. Both sites have 4 subareas (one for each crop: Subarea 1 = *Climacoptera lanata*, **subarea 2 = Medicago sativa, subarea 3 =** *Atriplex nitens*, **subarea 4 =** *Salicornia europeae***)**

	Khorezm				**Kyzylkezek**			
	Subarea Number				**Subarea Number**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
CNUM	60	60	60	60	61	61	61	61
INPS	3487	3487	3487	3487	3489	3491	3488	3490
IOPS	144	145	142	143	144	145	142	143
LCNO	0	0	0	0	1	1	1	1
IOW	4	4	4	4	4	4	4	4
II	0	0	0	0	0	0	0	0
IAPL	0	0	0	0	0	0	0	0
NVCN	0	0	0	0	0	0	0	0
WITH	110	110	110	110	111	111	111	111
SNO	0	0	0	0	0	0	0	0
STDO	0	0	0	0	0	0	0	0
LONG	64.865	64.865	64.865	64.865	64.865	64.865	64.865	64.865
LAT	41.094	41.094	41.094	41.094	41.094	41.094	41.094	41.094
AZM	0	0	0	0	0	0	0	0
WSA	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
CHL	0.25	0.25	0.25	0.25	0.48	0.64	0.64	0.64
CHD	0	0	0	0	0	0	0	0
CHS	0	0	0	0	0.1	0.1	0.1	0.1
CHN	0.02	0.3	0.02	0.02	0.35	0.05	0.05	0.05
STP	0	0	0	0	0	0	0	0
SPLG	100	100	100	100	100	100	100	100
UPN	0.12	0.24	0.12	0.12	0.16	0.3	0.16	0.16
FFPQ	0	0	0	0	0	0	0	0

RCHL	0.5	0.25	0.25	0.25	0.48	0.32	0.32	0.32
RCHD	0	0	0	0	0	0	0	0
RCBW	0	0	0	0	0	0	0	0
RCTW	0	0	0	0	0	0	0	0
RCHS	0	0	0	0	0	0	0	0
RCHN	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
RCHC	0.29	0	0.3	0.3	0.24	0	0.25	0.19
RCHK	0	0	0	0	0	0	0	0
RFPW	0	0	0	0	0	0	0	0
RFPL	0	0	0	0	0	0	0	0
RSEE	0	0	0	0	0	0	0	0
RSAE	0	0	0	0	0	0	0	0
RSVE	0	0	0	0	0	0	0	0
RSEP	0	0	0	0	0	0	0	0
RSAP	0	0	0	0	0	0	0	0
RSVO	0	0	0	0	0	0	0	0
RSV	0	0	0	0	0	0	0	0
RSYS	0	0	0	0	0	0	0	0
RSYN	0	0	0	0	0	0	0	0
RSHC	0	0	0	0	0	0	0	0
RSDP	0	0	0	0	0	0	0	0
RSBD	0	0	0	0	0	0	0	0
ISAO	0	0	0	0	0	0	0	0
NIRR	0	0	0	0	0	0	0	0
IRR	2	2	2	2	2	2	2	2
IRI	0	0	0	0	0	0	0	0
IFA	0	0	0	0	0	0	0	0
LM	0	0	0	0	0	0	0	0
IFD	1	1	1	1	1	1	1	1
IDR	0	0	0	0	0	0	0	0
IDF1	0	0	0	0	0	0	0	0
IDF2	0	0	0	0	0	0	0	0
IDF3	0	0	0	0	0	0	0	0
IDF4	0	0	0	0	0	0	0	0
IDF5	0	0	0	0	0	0	0	0
BIR	0	0	0	0	0	0	0	0
EFI	0	0	0	0	0	0	0	0
VIMX	0	0	0	0	0	0	0	0

ARMN	0	0	0	0	0	0	0	0
ARMX	0	0	0	0	0	0	0	0
BFT	0	0	0	0	0	0	0	0
FNP4	0	0	0	0	0	0	0	0
FMX	0	0	0	0	0	0	0	0
DRT	0	0	0	0	0	0	0	0
FDSF	0	0	0	0	0	0	0	0
PEC	0	0	0	0	0	0	0	0
DALG	1	1	1	1	1	1	1	1
VLGN	0	0	0	0	0	0	0	0
COWW	0	0	0	0	0	0	0	0
DDLG	0	0	0	0	0	0	0	0
SOLQ	0	0	0	0	0	0	0	0
SFLG	0	0	0	0	0	0	0	0
FNP2	0	0	0	0	0	0	0	0
FNP5	0	0	0	0	0	0	0	0
IMW	0	0	0	0	0	0	0	0
URBF	0	0	0	0	0	0	0	0
PCOF	0	0	0	0	0	0	0	0
BCOF	0	0	0	0	0	0	0	0
BFFL	0	0	0	0	0	0	0	0
FIRG	0	0	0	0	0	0	0	0
FL	0	0	0	0	0	0	0	0
FW	0	0	0	0	0	0	0	0
ANGL	0	0	0	0	0	0	0	0
NY (1)	0	0	0	0	0	0	0	0
XTP (1)	0	0	0	0	0	0	0	0

Table 46: Soil file parameters, definitions, and acceptable ranges according to APEX user manual. Initial values are located in table 47. Italics indicate parameters included in the sensitivity analysis. Bold indicates sensitive parameter.

	units	**range**	**definition**
Z	m	0.01 to 10	Depth from the soil surface to the bottom of the layer
BD	*g/cm^3*	*0.5 to 2.5*	*Moist Bulk Density*
U	*m/m*	*0.01 to 0.5*	*Soil water content at wilting point*
FC	*m/m*	*0.01 to*	*Soil Water content at field capacity*

		0.06	
SAN	*fraction*	*1 to 99*	*Sand content*
SIL	*fraction*	*1 to 99*	*Silt content*
WN	g N/Mg	100-5000	Initial organic N Concentration
PH		*3 to 9*	*The pH of a solution in equilibrium with soil*
SMB	*cmol/kg*	*0 to 150*	*Sum of bases.*
CBN	*%*		*Organic carbon concentration*
CAC	*%*	*0 to 99*	*Calcium carbonate content of soil*
CEC	*cmol/kg*	*0 to 150*	*Cation exchange capacity*
ROK	fraction	0 to 99	Coarse fragment content
CNDS	g/Mg	0.01 to 500	Initial soluble N concentration
O	g/Mg		Initial labile phosphorus concentration at the beginning of the simulation
RSD	*t/ha*		*Crop residue at beginning of simulation*
BDD	*g/cm^3*		*Bulk dry density (oven dry)*
PSP	*fraction*		*Phosphorus sorption ratio*
SC	*mm/h*		*Saturated conductivity*
HCL	mm/h	0.00001 to 10	Lateral hydraulic conductivity.
WP	g/Mg		Initial organic phosphorus concentration contained in humic substances for all soil layers at the beginning of the simulation
K	*fraction*		*Potassium concentration at the beginning of the simulation*
ECND	*mS/cm*	*0 to 50*	*Electrical Conductivity.*
STFR		*0.05 to 1*	*Fraction of storage interacting with Nitrate leaching*
CPRV		0 to 0.5	Fraction of inflow partitioned to verticle crack or pipe flow
CPRH		0 to 0.5	Fraction of inflow partitioned to horizontal crack or pipe flow
RT	mm		Return flow from groundwater storage

Table 47: Initial values for the soil in both the Khorezm and Kyzylkezek sites. Parameter definitions, and acceptable ranges according to the APEX User Manual are in Table 46.

	Khorezm (all)					**Kyzylkezek (*A. nitens*)**					**Kyzylkezek (*C. lanata*)**					**Kyzylkezek (*S. europeae*)**					**Kyzylkezek (*alfalfa*)**				
	Layer Number					**Layer Number**					**Layer Number**					**Layer Number**					**Layer Number**				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Z	0.2	0.4	0.6	0.8	1	0.2	0.4	0.6	0.8	1	0.2	0.4	0.6	0.8	1	0.2	0.4	0.6	0.8	1	0.2	0.4	0.6	0.8	1
BD	1.4	1.4	1.4	1.4	1.4	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
U	0.23	0.2	0.2	0.2	0.23	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.1	0.1	0.1	0.1	0.1	0.12	0.12	0.12	0.12	0.12
FC	0.38	0.4	0.4	0.4	0.38	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.25	0.25	0.25	0.25	0.25
SAN	10	10	10	10	10	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
SIL	90	90	90	90	90	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
WN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PH	7.49	7.7	7.8	7.7	7.72	7.51	7.58	7.6	7.61	7.55	7.51	7.58	7.6	7.61	7.55	7.4	7.4	7.5	7.4	7.4	7.59	7.66	7.68	7.69	7.63
SMB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CBN	1.18	1.2	1.2	1.2	1.18	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.4	0.4	0.4	0.4	0.4	0.44	0.44	0.44	0.44	0.44
CAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CEC	18.6	7.1	5.2	5.3	3.77	8.72	8.72	8.72	8.72	8.72	8.72	8.72	8.72	8.72	8.72	8.7	8.7	8.7	8.7	8.7	8.72	8.72	8.72	8.72	8.72
ROK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CNDS	15.5	8.7	6.9	4.5	4.4	21.4	15.1	15.6	16	11.4	21.4	15.1	15.6	16	11.4	22	31	25	28	39	6.1	4.2	4.4	4.2	3.3
O	8.8	3.5	3.5	3.2	4.7	48.3	21	17.8	14.6	49.3	48.3	21	17.8	14.6	49.3	15	7.6	8.4	6.5	5.3	9.9	5.2	2	3.8	10.1
RSD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BDD	1.2	1.2	1.2	1.2	1.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
PSP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC	0	0	0	0	0	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
HCL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K	132	94	94	80	108	583	391.8	360.9	355.7	294.4	583	391.8	360.9	355.7	294.4	5.1	3.1	3.6	3.1	3.3	345.6	156.6	138.5	132.5	175
ECND	3	1	1	1	1	2	1	1	4	0	2	1	1	4	0	8	7	5	6	6	1	1	0	0	0
STFR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CPRV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CPRH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 48: Soil list parameters and initial values for *Atriplex nitens* (ATNI), *Climacoptera lanata* (CLLA), *Salicornia europeae* (SAEU), and Medicago sativa (alf).

	units	range	Kho (all)	Kyz (ATNI)	Kyz (CLLA)	Kyz (SAEU)	Kyz (alf)	definition
SALB	ratio	0 to 1	0.16	0.12	0.12	0.12	0.12	Soil albedo
WTMN	m	0 to 100	0	0	0	0	0	Water table minimum
WTMX	m	0 to 100	0	0	0	0	0	Water table maximum
WTBL	m	0 to 100	0	0	0	0	0	current water level

Appendix B: APEX Weather Calculations

B.1 Precipitation

A Boolean value was chosen for each day in the data set to indicate if the day had any precipitation (1=yes, 0=no), if the day had no precipitation and was a valid (meaning that it contained data) (1=yes, 0=no), if the current day and the preceding day contained precipitation (1=yes, 0=no), and if the current day contained precipitation but the preceding day did not (1=yes, 0=no). The average number of days with rain in a month was calculated by summing the number of days with precipitation for each valid month in each year, and then averaging it over the number of valid years of data that month had. The probability that a wet day follows a dry day was calculated by

$$P(today\ is\ wet \mid yesterday\ was\ dry) = (W_D)/(DD_V) \tag{9}$$

where W_D is the sum of Boolean values for wet day following a dry day and DD_V is the sum of Boolean values for the number of dry and valid days. The probability that a wet day follows a dry day was calculated by:

$$P(today\ is\ wet \mid yesterday\ was\ wet) = (W_W)/(WD) \tag{10}$$

where W_W is the sum of Boolean values for wet day following a wet day and WD is the sum of Boolean values for the number of wet days.

B.2 Wind

APEX divides wind direction into 16 different directions (N, NNE, NE, ENE, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW). The data contained daily average wind direction in degrees (values between 0 and 360), so each of the 16 wind directions were divided up with a high and low that described the boundaries for the wind direction (Table 49). A Boolean value for each day and each wind direction was created with 0 if the day's average wind direction did not fall into that zone, and 1 if it did. If the average wind speed was exactly on one of the boundaries, it was categorized into the lower section (ie. an average wind direction of 101.25 degrees was classified as being E). The Boolean values were summed for each month (regardless of year), which gave the total number of days in the data set that had average wind directions in each of the 16 sections. The total number of days (regardless of year) with data for wind direction was found for each month. The probability that wind comes from each direction was calculated by dividing the Boolean value for each month and direction by the total number of days with data for each month.

Table 49: Wind directions with the upper and lower boundaries (in degrees).

	lower	upper
N	348.75	11.25
NNE	11.25	33.75
NE	33.75	56.25
ENE	56.25	78.75
E	78.75	101.25
ESE	101.25	123.75
SE	123.75	146.25
SSE	146.25	168.75
S	168.75	191.25
SSW	191.25	213.75
SW	213.75	236.25
WSW	236.25	258.75
W	258.75	281.25
WNW	281.25	303.75
NW	303.75	326.25
NNW	326.25	348.75

Appendix C: Sensitivity Analysis

Table 51 contains the values that were used for each parameter in the sensitivity analysis. Each run in the sensitivity analysis changed only one parameter. See Appendix A for definitions of parameters.

Table 50: Sensitivity analysis ranges and input values at percentages of the range.

Parameter	Range		Percent of range				
	Low	High	0%	25%	50%	75%	100%
TEXTID							
HYDGRP	1	4	1	2	3	4	n/a
BD	0.5	2.5	0.5	1	1.5	2	2.5
U	0.01	0.5	0.01	0.1325	0.255	0.3775	0.5
FC	0.01	0.06	0.01	0.0225	0.035	0.0475	0.06
SAN	1	99	1	25.5	50	74.5	99
SIL	1	99	1	25.5	50	74.5	99
PH	3	9	3	4.5	6	7.5	9
K	0	1	0	0.25	0.5	0.75	1
STFR	0.05	1	0.05	0.2875	0.525	0.7625	1
PSP	0	1	0	0.25	0.5	0.75	1
RSD	0	20	0	5	10	15	20
SMB	0	150	0	37.5	75	112.5	150
CAC	0	99	0	24.75	49.5	74.25	99
CBN	1	99	1	25.5	50	74.5	99
CEC	0	150	0	37.5	75	112.5	150
BDD	0.5	2	0.5	0.875	1.25	1.625	2
SC	0.00001	100	0.00001	25.00001	50.00001	75	100
ECND	0	50	0	13	25	38	50
SALB	0	1	0	0.25	0.5	0.75	1
WTMN	0	100	0	25	50	75	100
WTMX	0	100	0	25	50	75	100
lower slope	0	5	0	1.25	2.5	3.75	5
upper slope	0	5	0	1.25	2.5	3.75	5
WTBL	0	100	0	25	50	75	100
CQNO	1	9999	1	2500.5	5000	7499.5	9999

DIAM	100	500	100	200	300	400	500
RTNO	1	10	1	3	5	8	10
CSLT	0	50000	0	12500	25000	37500	50000
WSA	0.1	5	0.1	1.325	2.55	3.775	5
WA	1	99	1	25.5	50	74.5	99
DMLA	0	20	0	5	10	15	20
DLAPI	1	100	1	25.75	50.5	75.25	100
DLAP2	1	100	1	25.75	50.5	75.25	100
GSI	0.001	0.05	0.001	0.01325	0.0255	0.03775	0.05
RDMX	0.1	5	0.1	1.325	2.55	3.775	5
WAVP	2	15	2	5.25	8.5	11.75	15
RWPC1	0.2	0.6	0.2	0.3	0.4	0.5	0.6
RWPC2	0.1	0.9	0.1	0.3	0.5	0.7	0.9
STX1	0	0.5	0	0.125	0.25	0.375	0.5
STX2	0	20	0	5	10	15	20
SLTY	0	0.1	0	0.025	0.05	0.075	0.1
HI	0	2	0	0.5	1	1.5	2
HMX	0.16	4	0.16	1.12	2.08	3.04	4
CPY	0.0003	12	0.0003	3.000225	6.00015	9.000075	12
CKY	0	150	0	37.5	75	112.5	150
WCY	0.0073	0.96	0.0073	0.245475	0.48365	0.721825	0.96

Appendix D: Sensitivity Analysis Run Instructions

Below are directions on how to perform the sensitivity analysis. The sensitivity analysis used macros that were written into an excel sheet. These instructions are to be used with file Sensitivity.xlsm.

1) Change all parameters based on what Run number it is. The parameter change is documented for each run in the tab 'Bookkeeping'

- Open the Access file located in C://WinAPEX named TEXAS CENTRAL.mdb
- Open the file (indicated on leftmost column) for the parameter that will be changed
- For "soil data" scroll all of the way to the bottom
    - change parameter for ALL of the soils that are listed. Take note that TEXTID and HYDGRP need to be changed in both the Soil Data and Soil List files.
- For "soil list" scroll all of the way to the bottom

2) "Crop" parameters must be changed in the text file (or .dat) located in “Jaehak files” in the sensitivity file.

3) Open WinAPEX icon on the desktop

- If odd number run, select watershed "Kyzylkezek" and control file "Kyzyl"
- If even number run, select watershed "Khorezm" and control file "Khorezm"
- Run WinApex (ignore "Error in one or more of the output files")

4) Open C://WinApex/aprexprog

- Copy all files (do not include folders)

5) Open C://WinApex/Sensitivity

- Paste all files. Select copy and replace for all files (check the box in lower left)
- Open Folder "Jaehak Files"
    - Copy all files
    - Paste all files in Sensitivity. Select copy and replace for all files (check the box in lower left)
- Find APEX0806-salt.exe
    - Double click to run salinity module.

6) Go to tab "Runs" on this excel sheet.

- Enter the Run number (VERY important)
- Below the run number, it will tell you if it is Kyzylkezek or Khorezm
- Hit all of the buttons in order for Kyzylkezek or Khorezm
- **SAVE**

7) Repeat for all Soil, Soil List, and Crop parameter runs.

8) Change parameter back to initial values when done with run.

9) Parameters CQNO, DIAM, RTNO, and CSLT can be found in the Control File which must be changed through the APEX interface.

- Open APEX icon on desktop
- Select “Add/Edit Control Files”
- Select “Edit Records”

- Select drop down bod for Kyzyl or Khorezm
- Find parameter and put new value in “New column”
- Press Enter
- Select “Save” and exit out.
- Go through steps 3-5, and 7.

10) Parameter WSA is located in the Subarea file which must be changed through the APEX interface.

- Open APEX icon on desktop
- Select “Edit Watershed Files”
- Select the drop down box for Khorezm or Kyzylkezek depending on run number
- Select “Edit SubArea”
- Find parameter, and change for all 4 subareas.
- Select “Save” and exit out.
- Go through steps 3-5, and 7.

Appendix E: Calibration Run Directions

Below are instructions on how to perform the calibration runs. Khorezm and Kyzylkezek have different folders and different excel files. Khorezm runs are to be done in C://WinAPEX/Calibration/Khorezm using the Khorezm.xlsm file, and Kyzylkezek runs are to be done in C://WinAPEX/Calibration/Kyzylkezek using the Kyzyl.xlsm file.

1) Open Khorezm.xlsm or Kyzyl.xlsm.
2) Enter the run number
3) Press Step 2: Khorezm or Step 2: Kyzylkezek. This step groups 3 macros. The first copies the random parameter values created in sheet entitled “Random” to the Sheet named “Khorezm Runs” or “Kyzyl Runs.” The second macro copies the randomly created crop parameters from “Khorezm Runs” or “Kyzyl Runs” into crop.xlsm. The third macro takes the values from crop.xlsm and copies them to the clipboard with the proper spacing for APEX to be able to read them
4) Open a blank notepad (*.txt) file, and control paste. Save this file as “crop.dat” in either the Khorezm or Kyzylkezek folder. Click yes to overwrite the existing crop.dat file.
5) Press Step 4: Khorezm or Step 4: Kyzyl. This macro takes the randomly created crop file parameters in sheet “Khorezm Runs” or “Kyzyl Runs” and saves them as “3487.prn” for Khorezm or “3488, 3489, 3490, and 3491” for Kyzylkezek (one for each unique soil). Click “yes” to replacing the existing *.prn file and “save” the changes to the *.prn file 1 time for Khorezm, and 4 times for Kyzylkezek.

6) Go to either the Khorezm or Kyzylkezek folder, locate “Khorezm.py” or “Kyzyl.py” respectively. Double click. This step is a python code that will change the “*.prn” files into a text file that APEX is capable or reading. It will also run the executable
7) Click Step 6. This will transfer the statistical results (RMSE, rsqu, and %bias) into the “Results” sheet for each metric. It will also transfer the modeled verses observed results for each metric into each respective sheet.
8) Change the run number to the next run, and repeat this process 500 times for each location.

Appendix F: Sensitivity Analysis Graphs

These graphs show results from the sensitivity analysis. Five values of each parameter were tested within specified ranges of parameter values. Graphs on the left show results for all tested parameters for each date, species, and observed measurement. Graphs on the right only include sensitive parameters in which the deviation from observed values changed as parameter values changed.

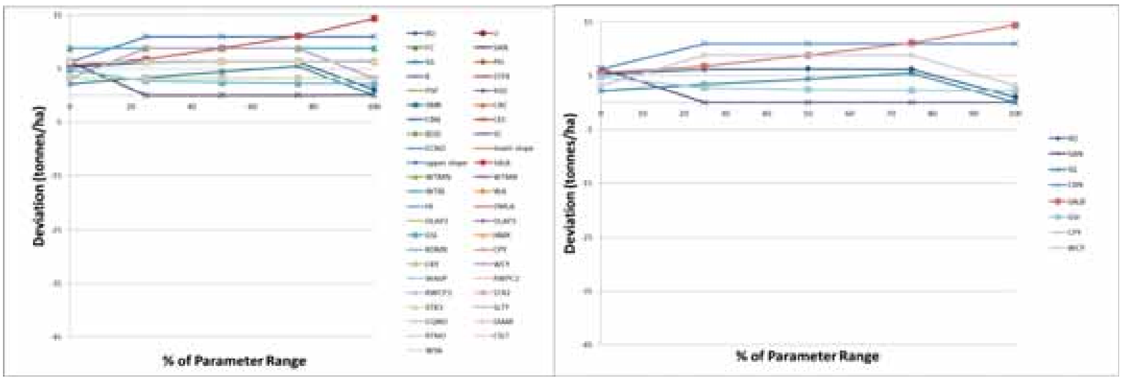

Figure 31: Biomass, Khorezm, Medicago sativa, 7/6/13

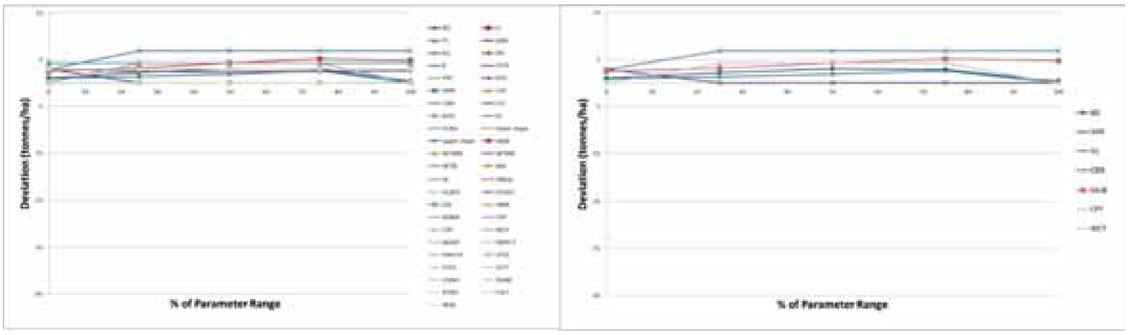

Figure 32: Biomass, Khorezm, *Atriplex nitens*, 7/6/13

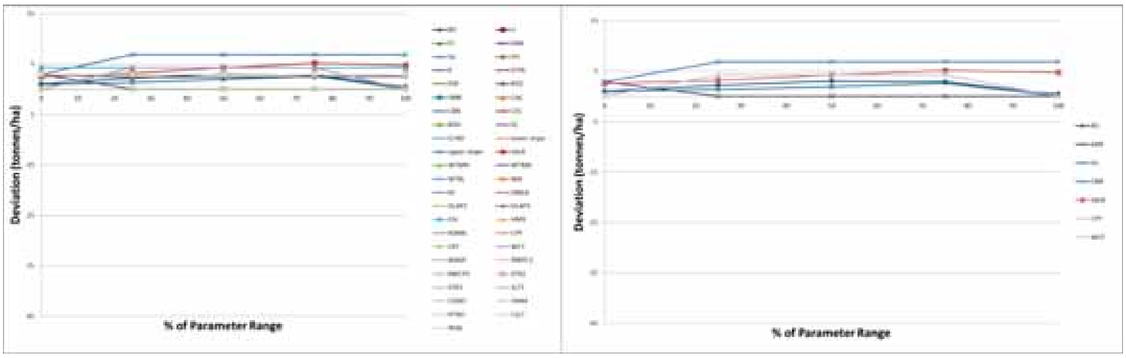

Figure 33: Biomass, Khorezm, *Atriplex nitens*, 10/12/13

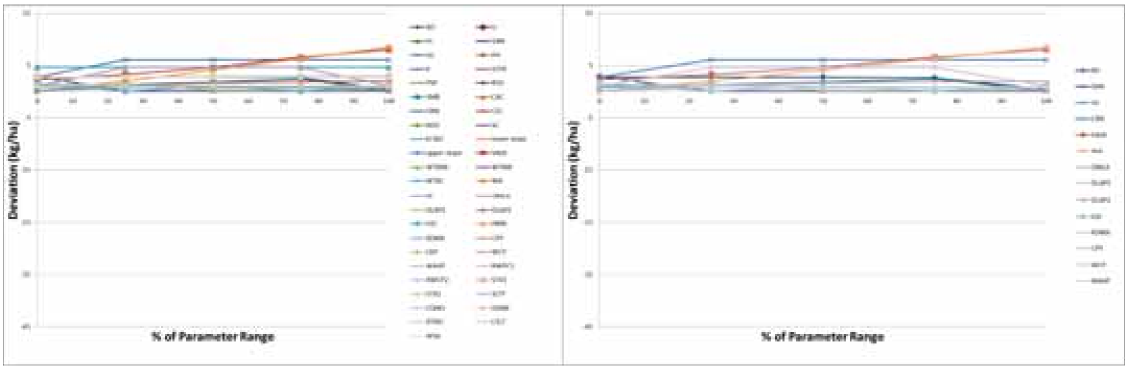

Figure 34: Biomass, Khorezm, *Climacoptera lanata*, 7/6/13

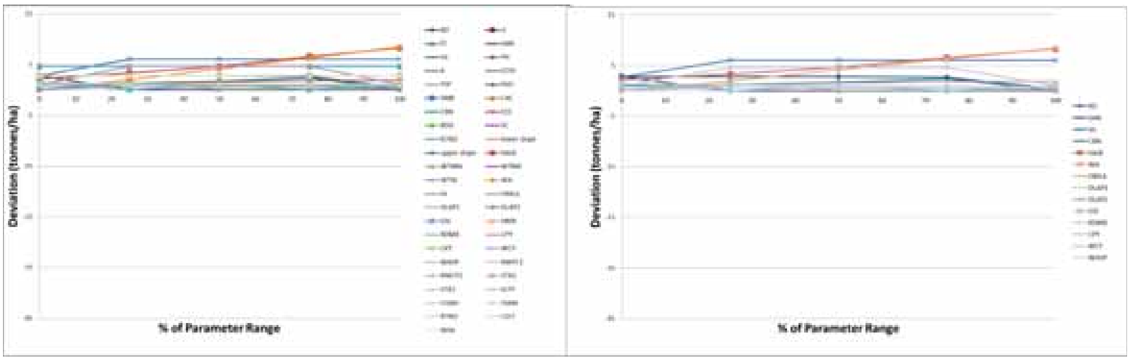

Figure 35: Biomass, Khorezm, *Climacoptera lanata*, 10/12/13

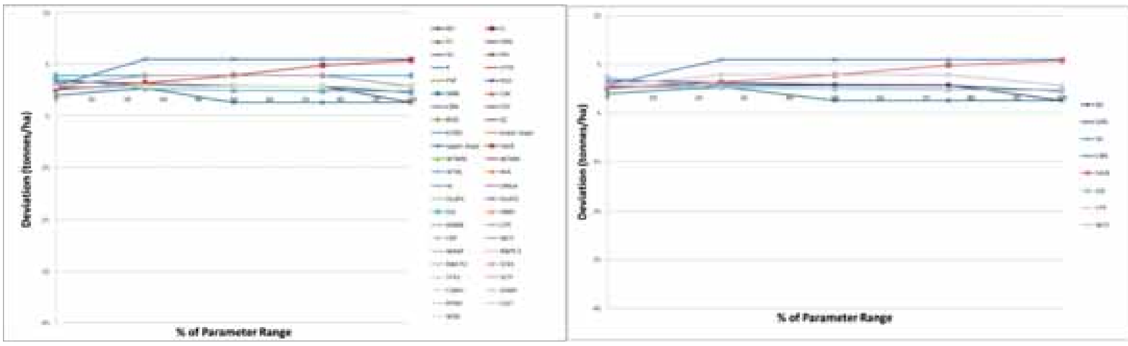

Figure 36: Biomass, Kyzylkezek, Medicago sativa, 7/6/13

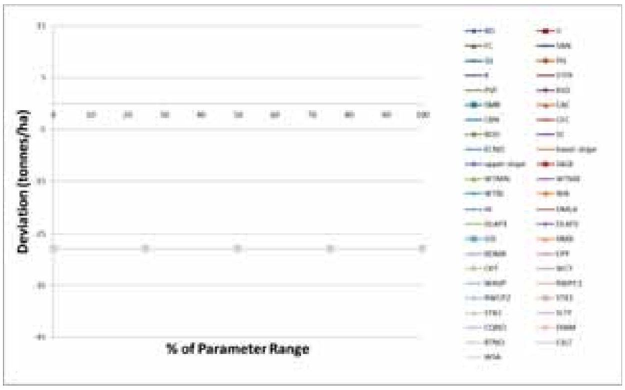

Figure 37: Biomass, Kyzylkezek, *Atriplex nitens*, 7/6/13

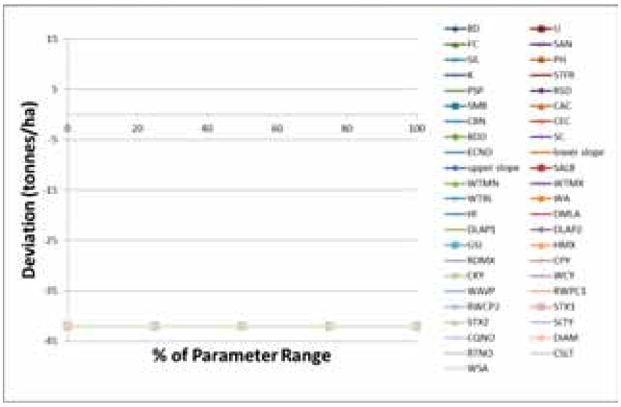

Figure 38: Biomass, Kyzylkezek, *Atriplex nitens*, 10/12/13

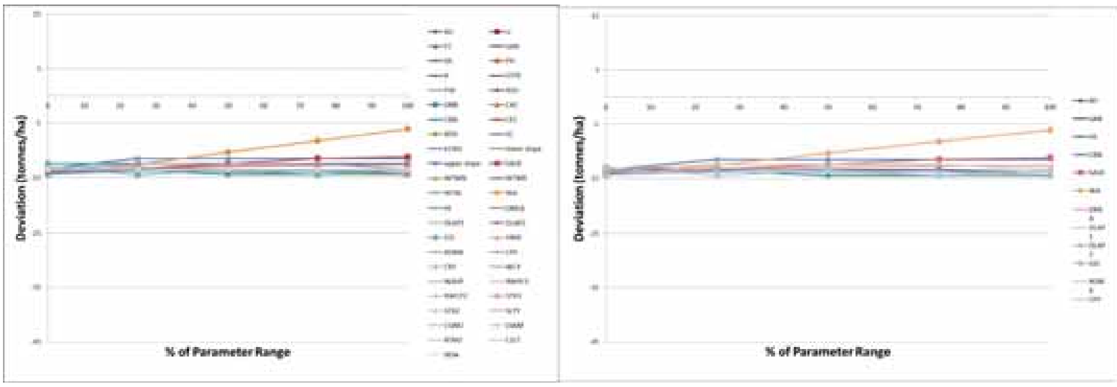

Figure 39:Biomass, Kyzylkezek, *Climacoptera lanata*, 7/6/13

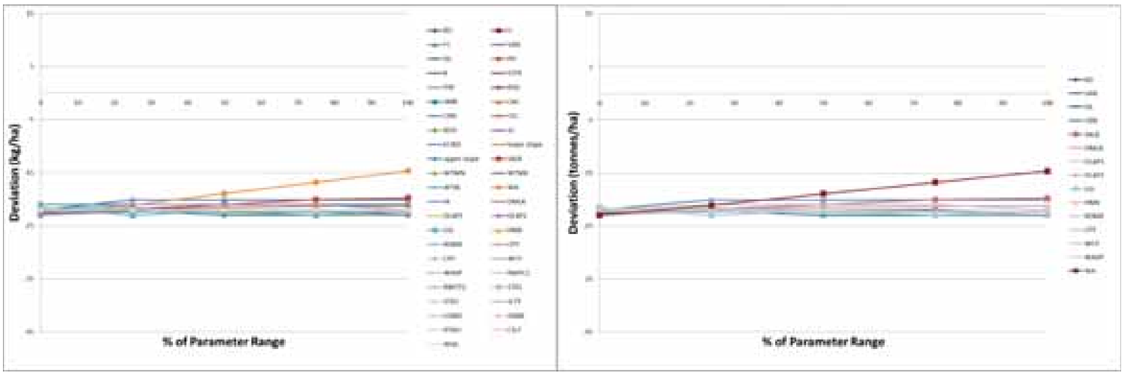

Figure 40: Biomass, Kyzylkezek, *Climacoptera lanata*, 10/12/13

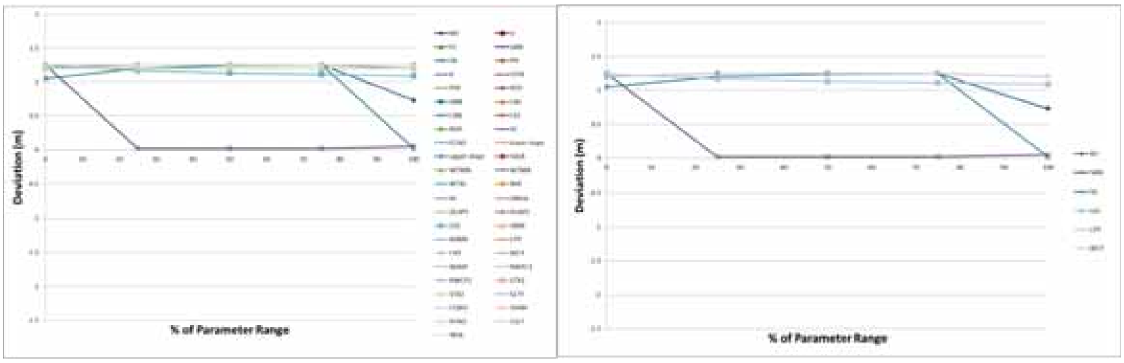

Figure 41: Crop height, Khorezm, Medicago sativa, 5/14/13

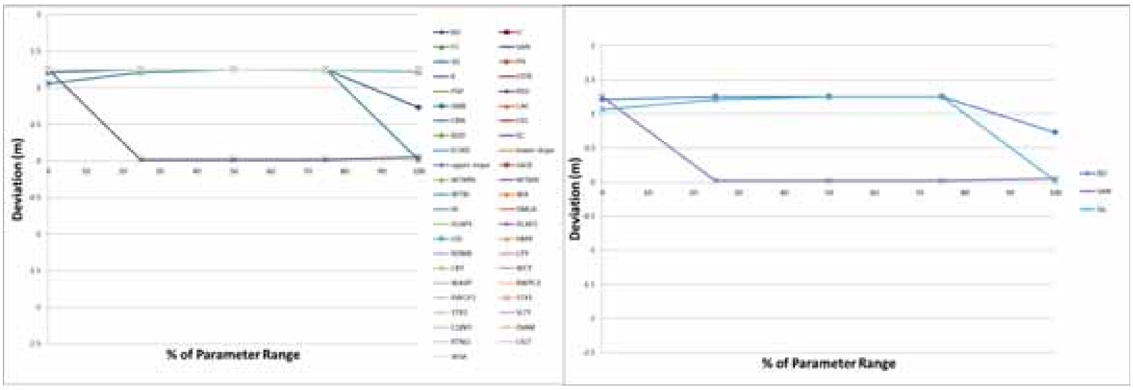

Figure 42: Crop height, Khorezm, Medicago sativa, 6/17/13

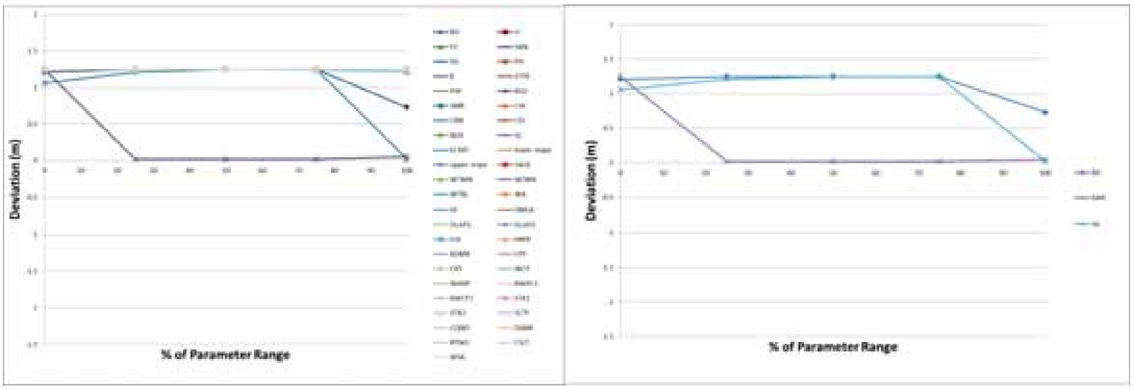

Figure 43: Crop height, Khorezm, Medicago sativa, 7/6/13

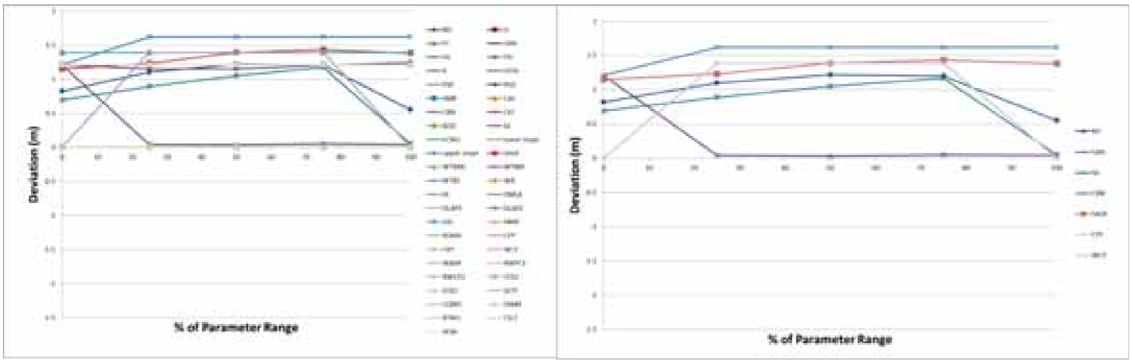

Figure 44: Crop height, Khorezm, *Atriplex nitens*, 5/14/13

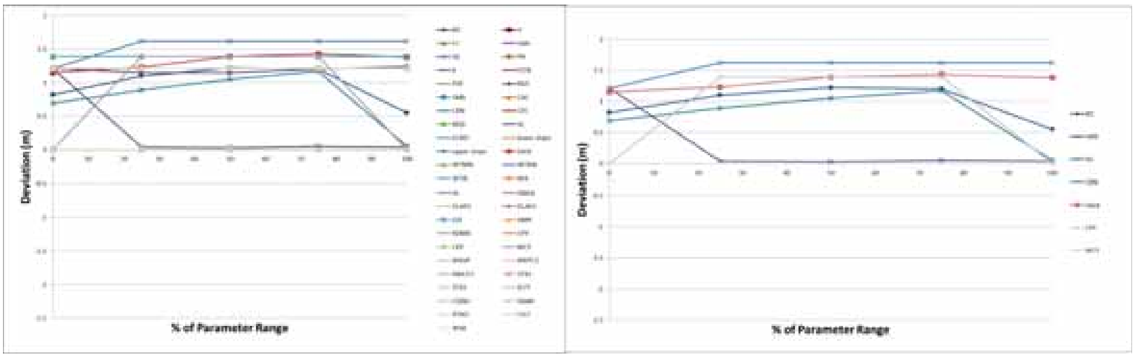

Figure 45: Crop height, Khorezm, *Atriplex nitens*, 6/17/13

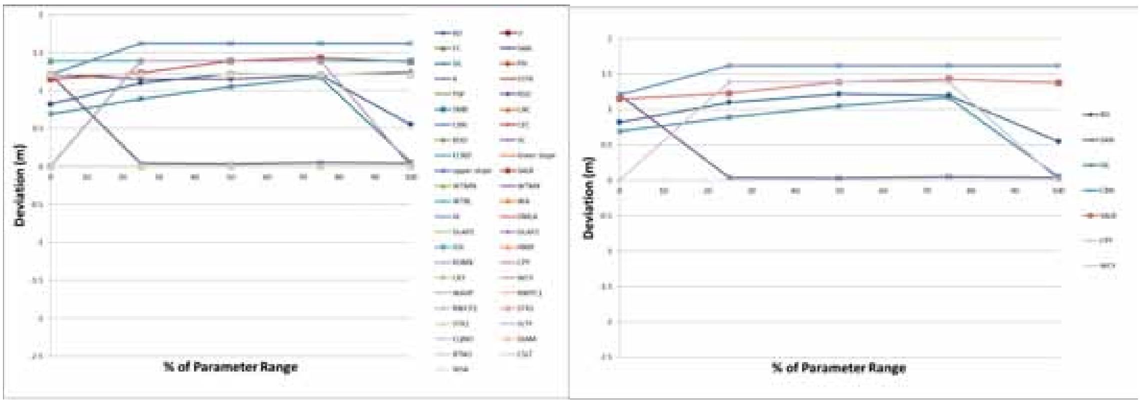

Figure 46: Crop height, Khorezm, *Atriplex nitens*, 7/6/13

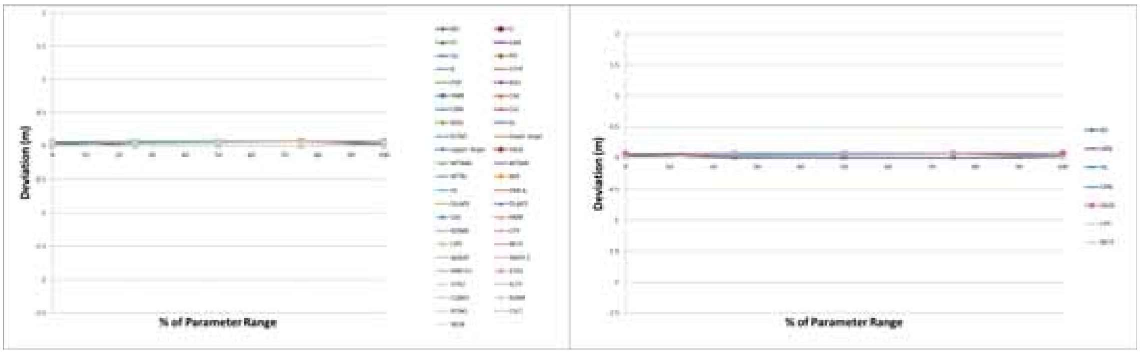

Figure 47: Crop height, Khorezm, *Atriplex nitens*, 10/12/13

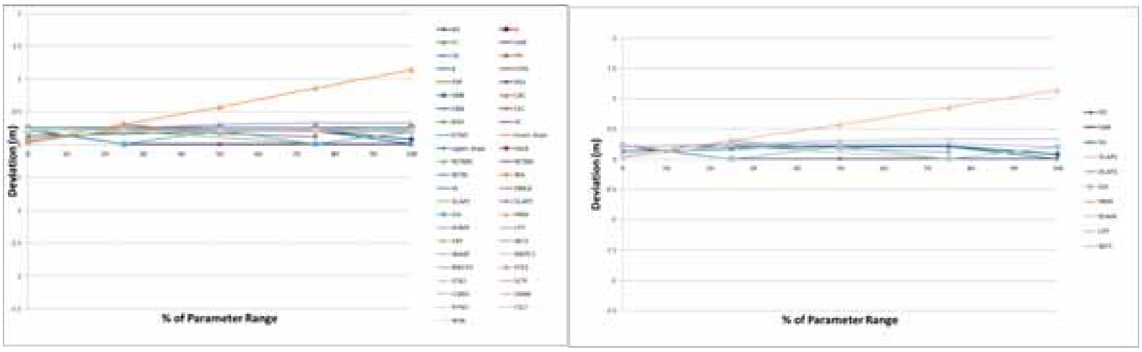

Figure 48: Crop height, Khorezm, *Climacoptera lanata*, 5/14/13

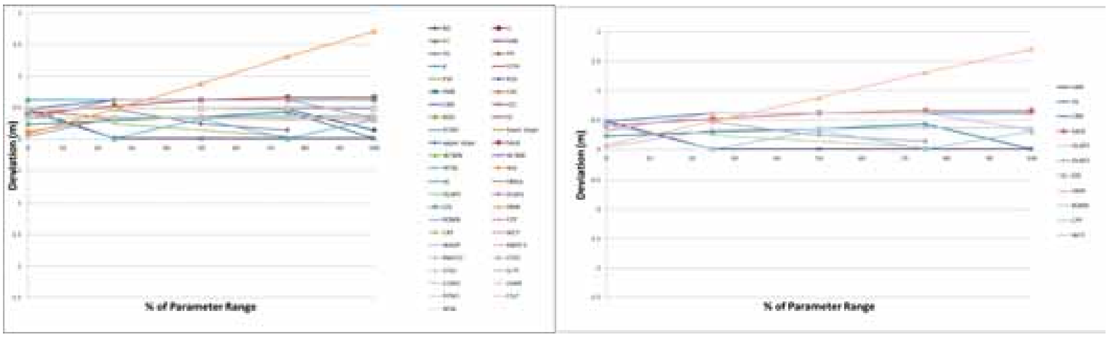

Figure 49: Crop height, Khorezm, *Climacoptera lanata*, 6/17/13

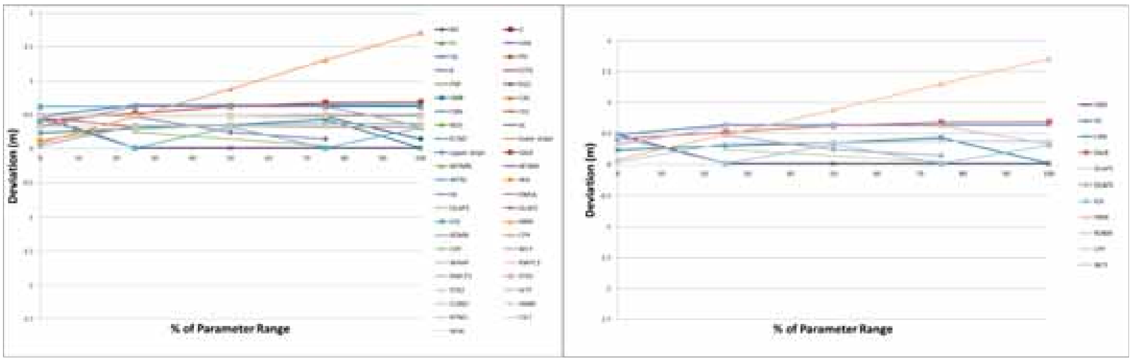

Figure 50: Crop height, Khorezm, *Climacoptera lanata*, 7/6/13

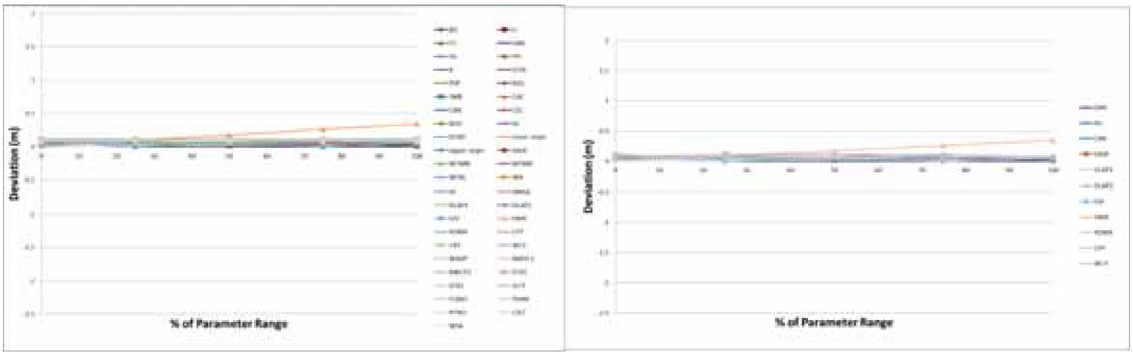

Figure 51: Crop height, Khorezm, *Climacoptera lanata*, 10/12/13

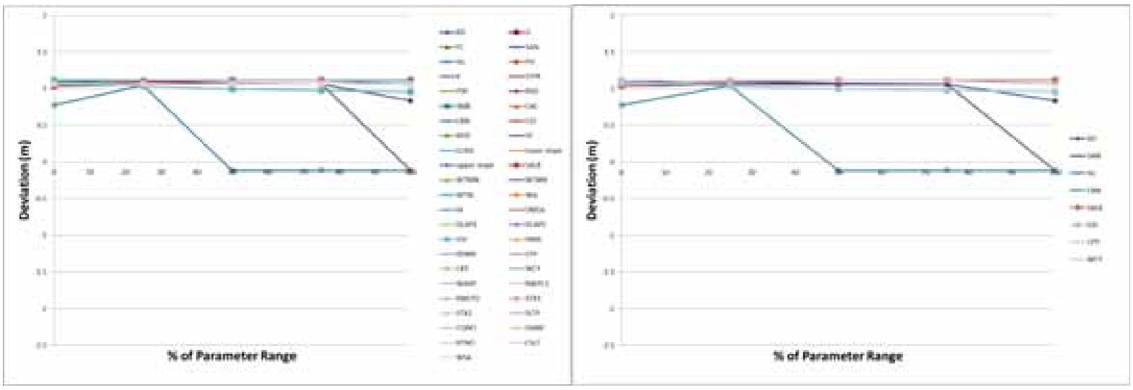

Figure 52: Crop height, Kyzylkezek, Medicago sativa, 5/14/13

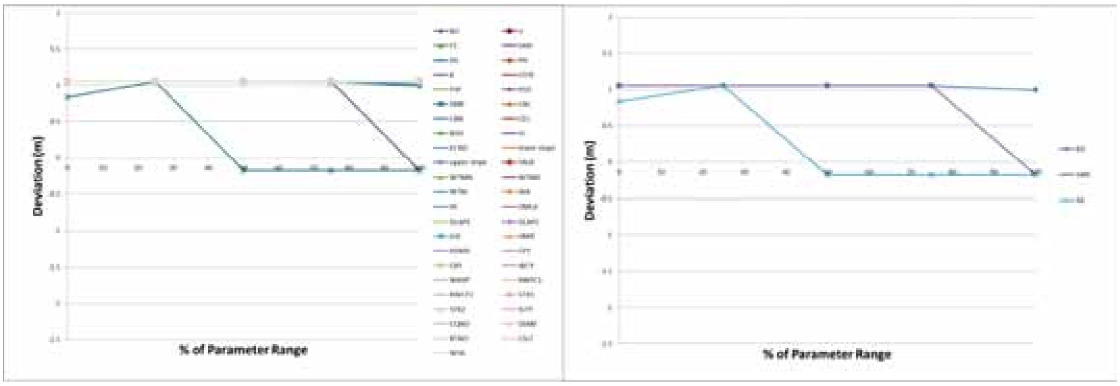

Figure 53: Crop height, Kyzylkezek, Medicago sativa, 6/17/13

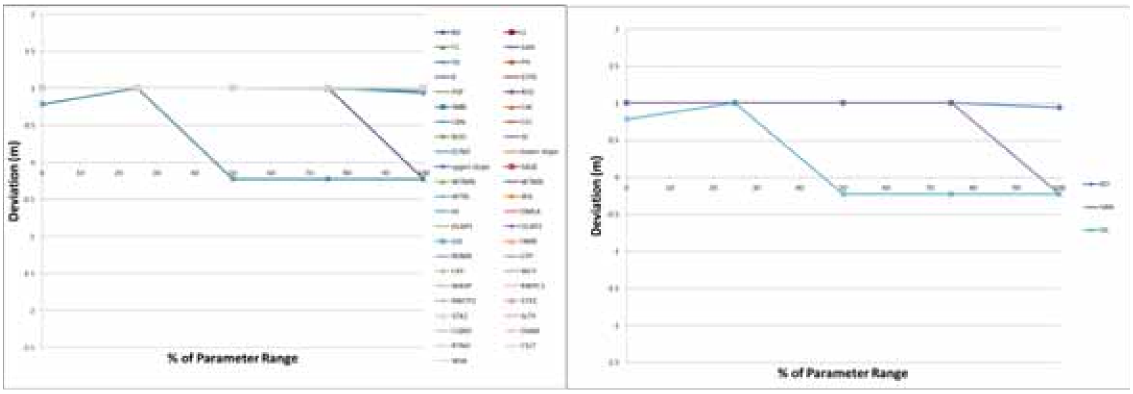

Figure 54: Crop height, Kyzylkezek, Medicago sativa, 7/6/13

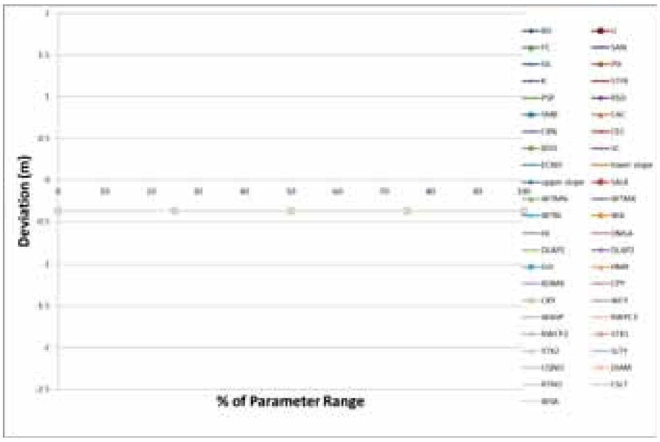

Figure 55: Crop height, Kyzylkezek, *Atriplex nitens*, 5/14/13

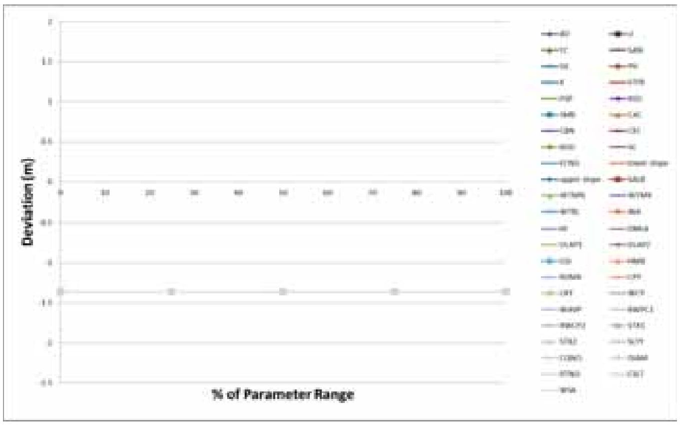

Figure 56: Crop height, Kyzylkezek, *Atriplex nitens*, 6/17/13

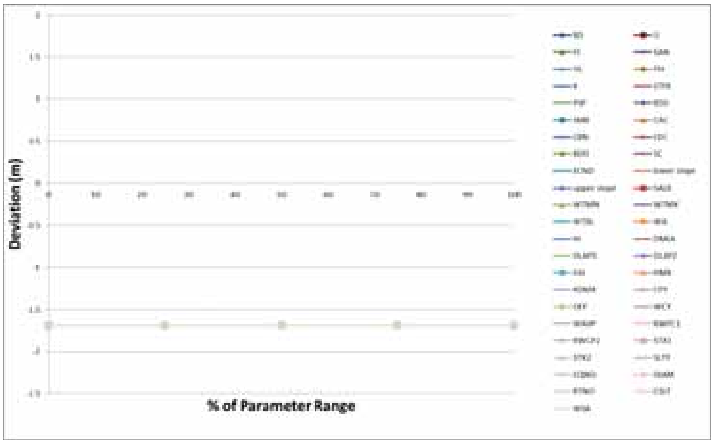

Figure 57: Crop height, Kyzylkezek, *Atriplex nitens*, 7/6/13

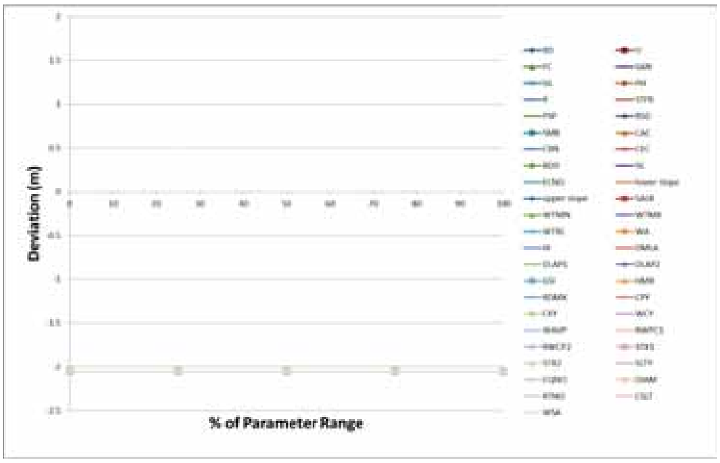

Figure 58: Crop height, Kyzylkezek, *Atriplex nitens*, 10/12/13

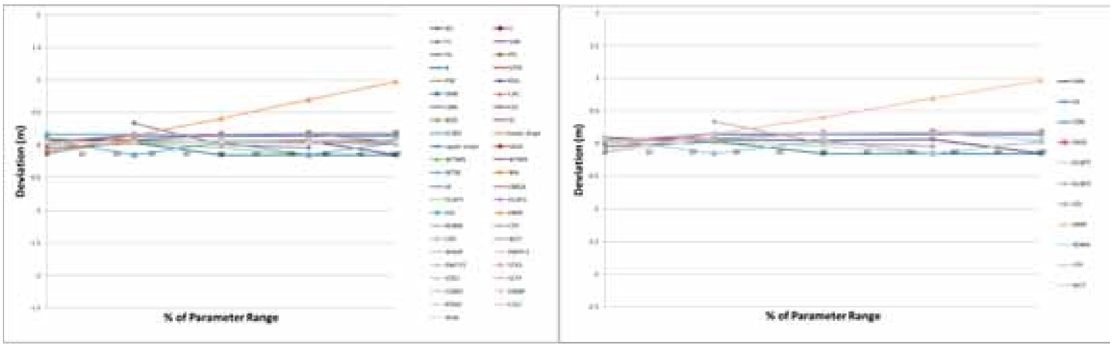

Figure 59: Crop height, Kyzylkezek, *Climacoptera lanata*, 5/14/13

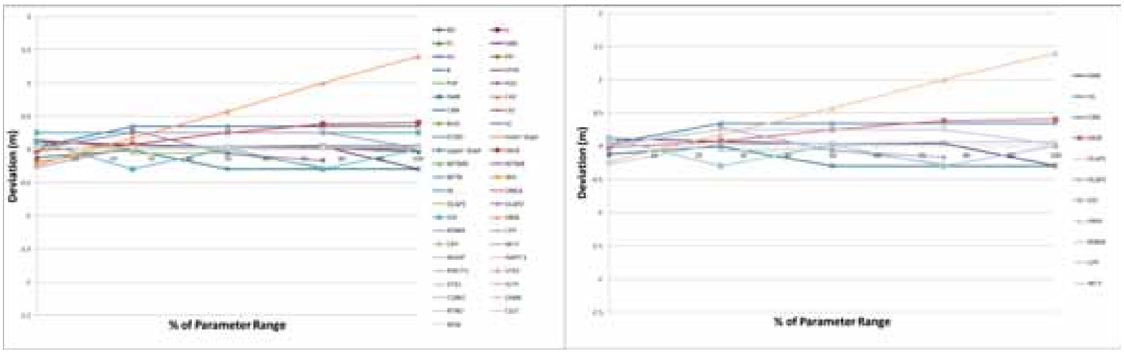

Figure 60: Crop height, Kyzylkezek, *Climacoptera lanata*, 6/17/13

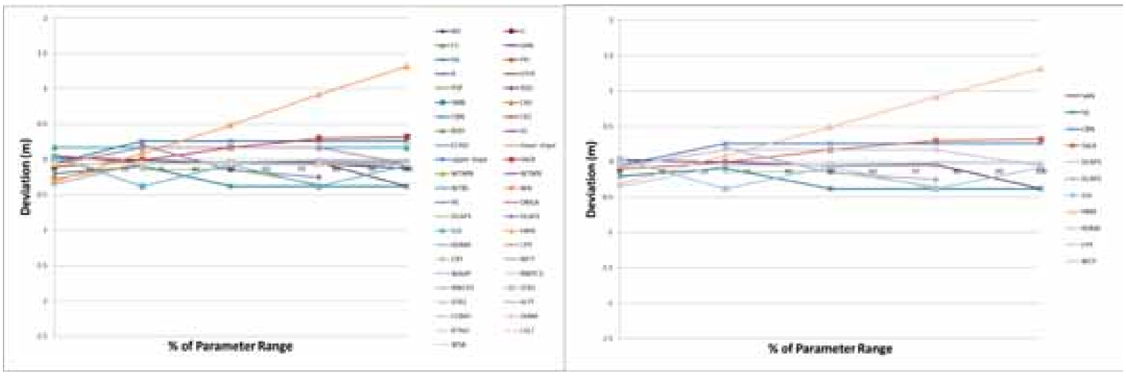

Figure 61: Crop height, Kyzylkezek, *Climacoptera lanata*, 7/6/13

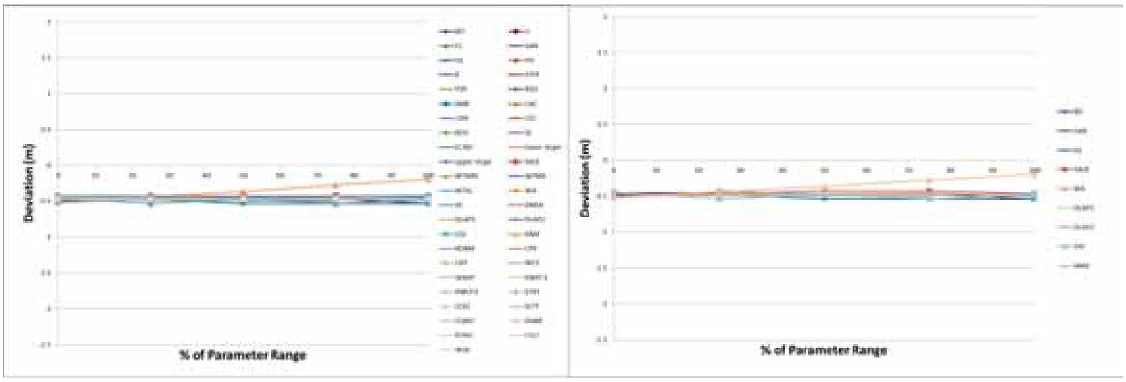

Figure 62: Crop height, Kyzylkezek, *Climacoptera lanata*, 10/12/13

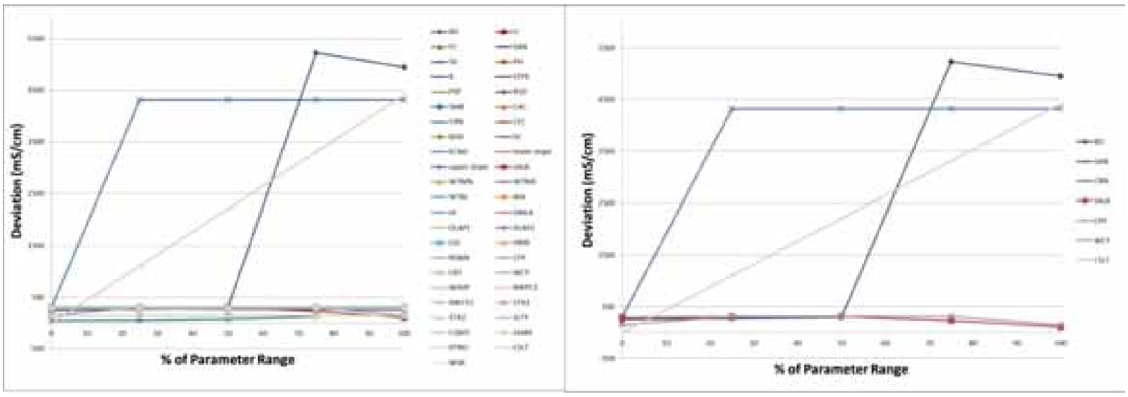

Figure 63: EC, Khorezm, *Atriplex nitens*, 6/15/13

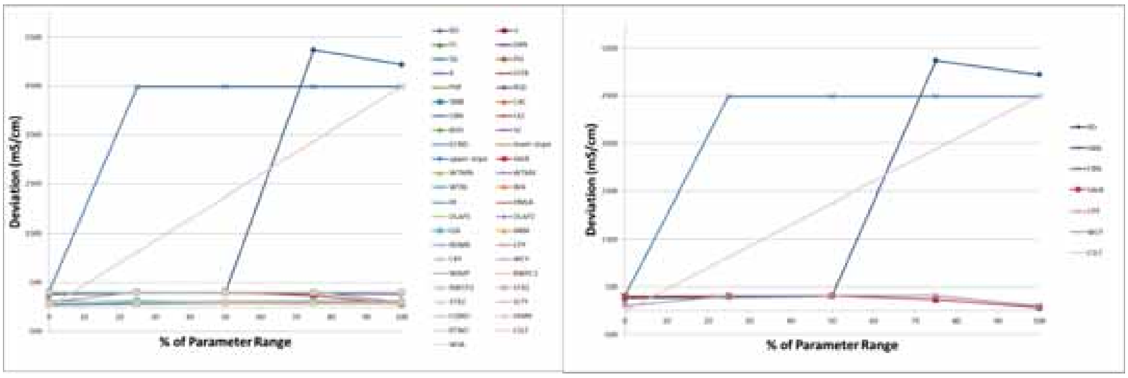

Figure 64: EC, Khorezm, *Climacoptera lanata*, 6/15/13

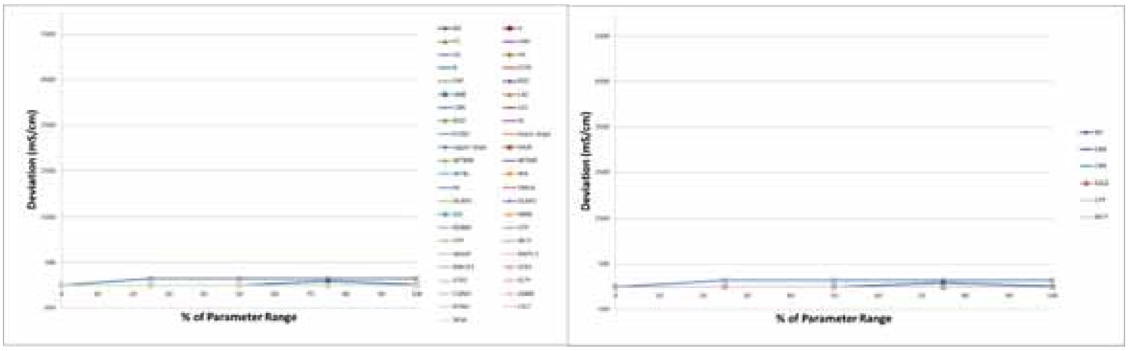

Figure 65: EC, Khorezm, *Salicornia europeae*, 6/15/13

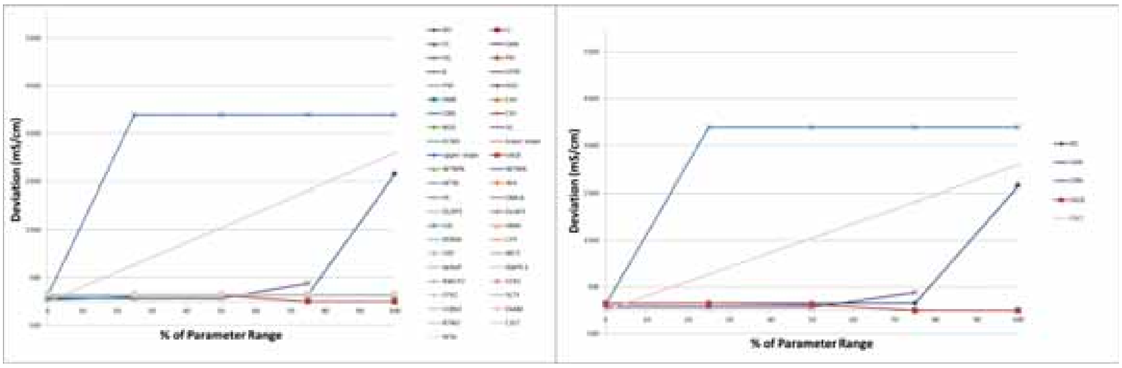

Figure 66: EC, Kyzylkezek, *Atriplex nitens*, 6/28/13

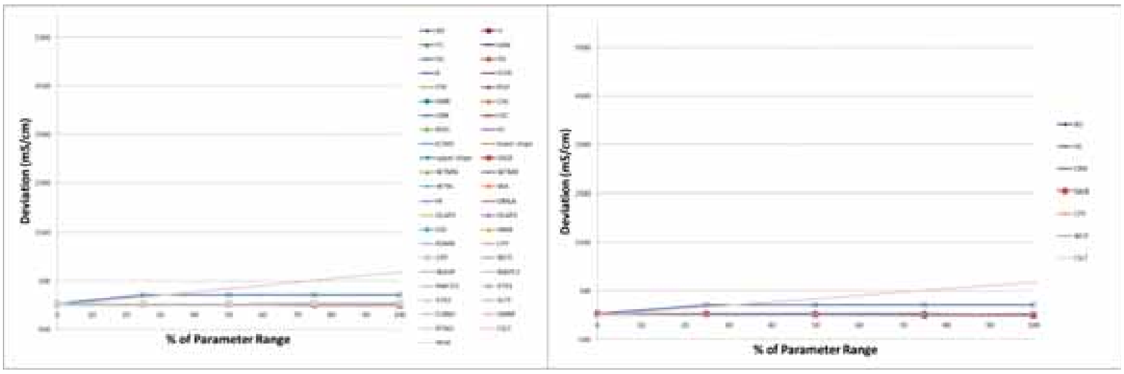

Figure 67: EC, Kyzylkezek, *Climacoptera lanata*, 4/14/13

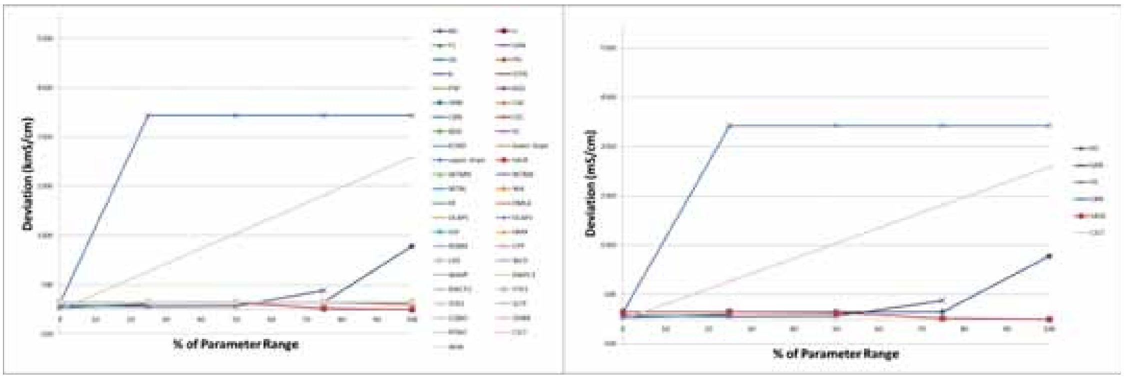

Figure 68: EC, Kyzylkezek, *Climacoptera lanata*, 8/4/13

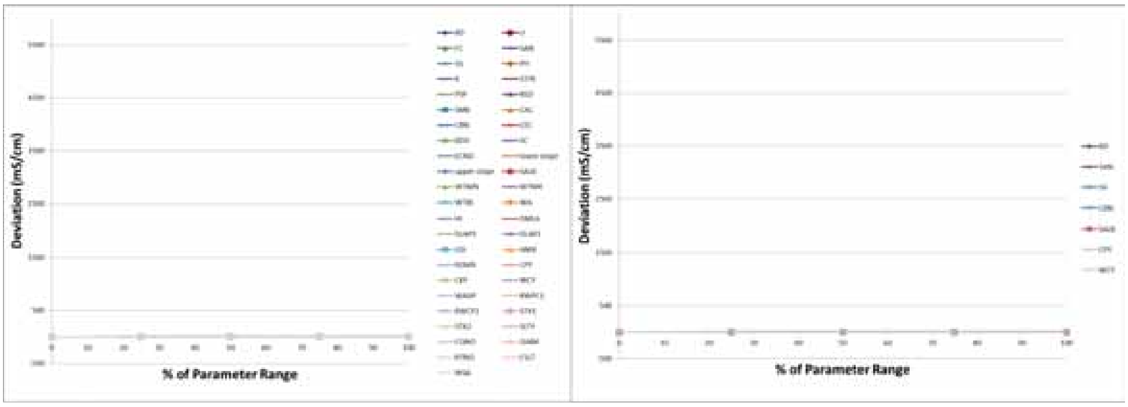

Figure 69: EC, Kyzylkezek, *Salicornia europeae*, 4/14/13

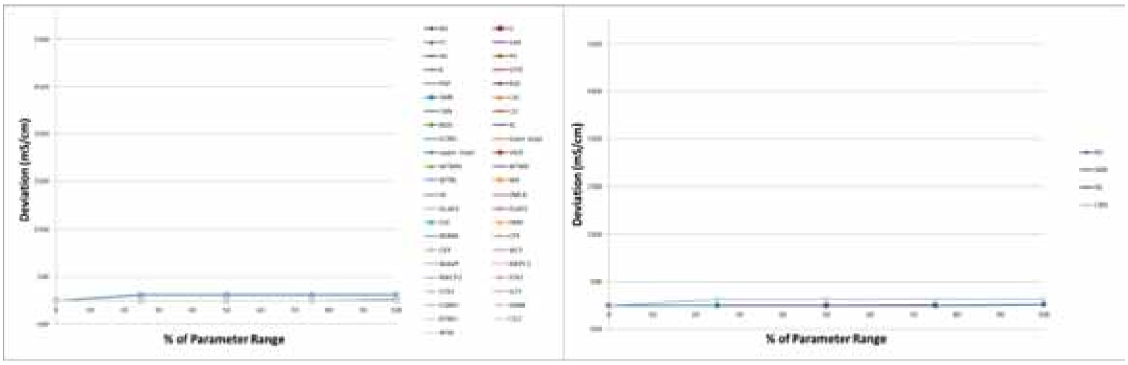

Figure 70: EC, Kyzylkezek, *Salicornia europeae*, 6/28/13

Appendix G: Calibrated Model Performance Graphs

These graphs compare observed versus modeled results for crop biomass, crop height, and soil EC for both Khorezm and Kyzylkezek.

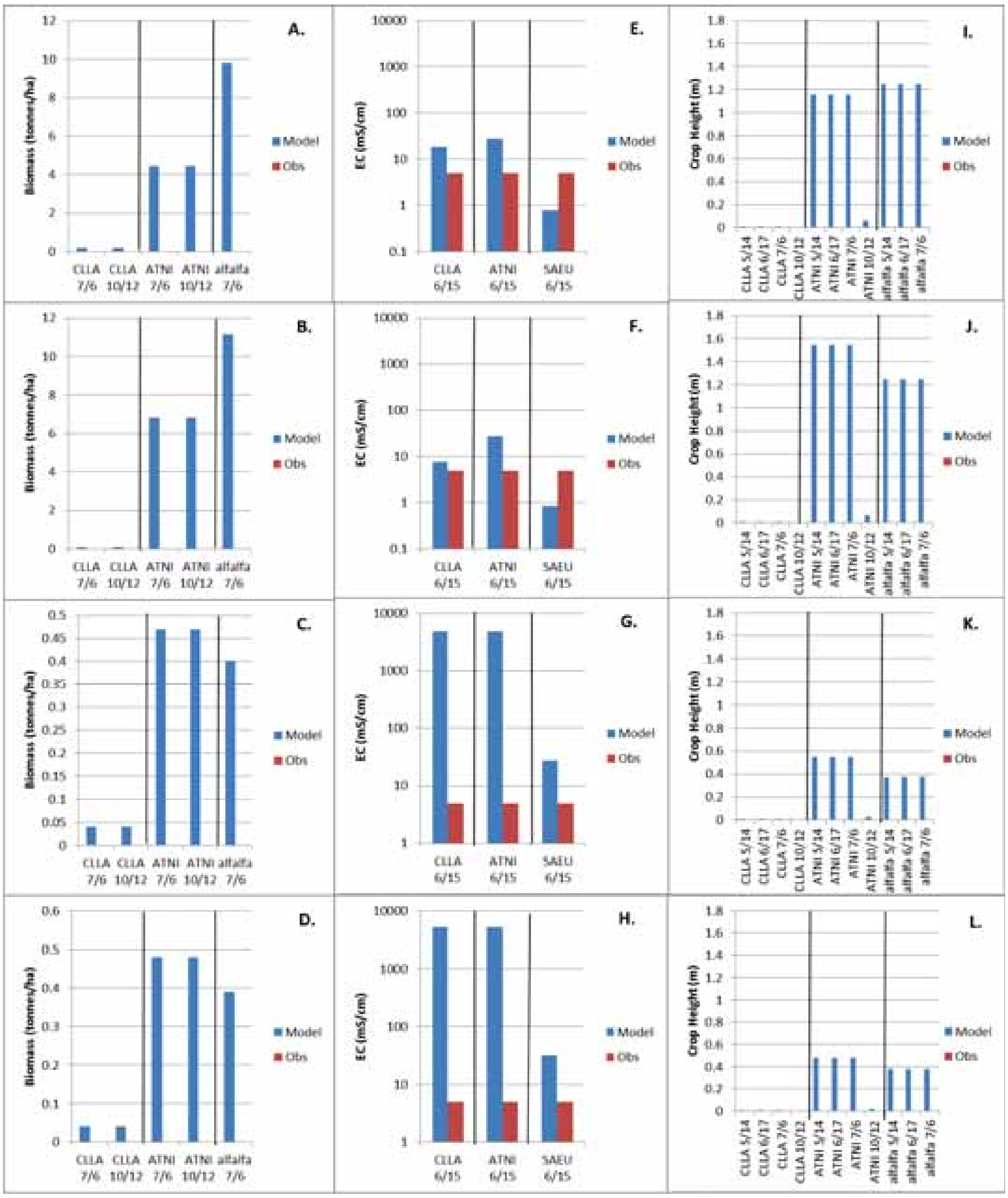

Figure 71: Khorezm modeled vs observed values for biomass (A. Best RMSE B. Best Soil EC RMSE C. Best Biomass RMSE, D. Best Crop Height RMSE), EC (E. Best RMSE F. Best Soil EC RMSE G. Best Biomass RMSE H. Best Crop Height RMSE), and Crop Height (I. Best RMSE J. Best Soil EC RMSE K. Best Biomass RMSE L. Best Crop Height RMSE)

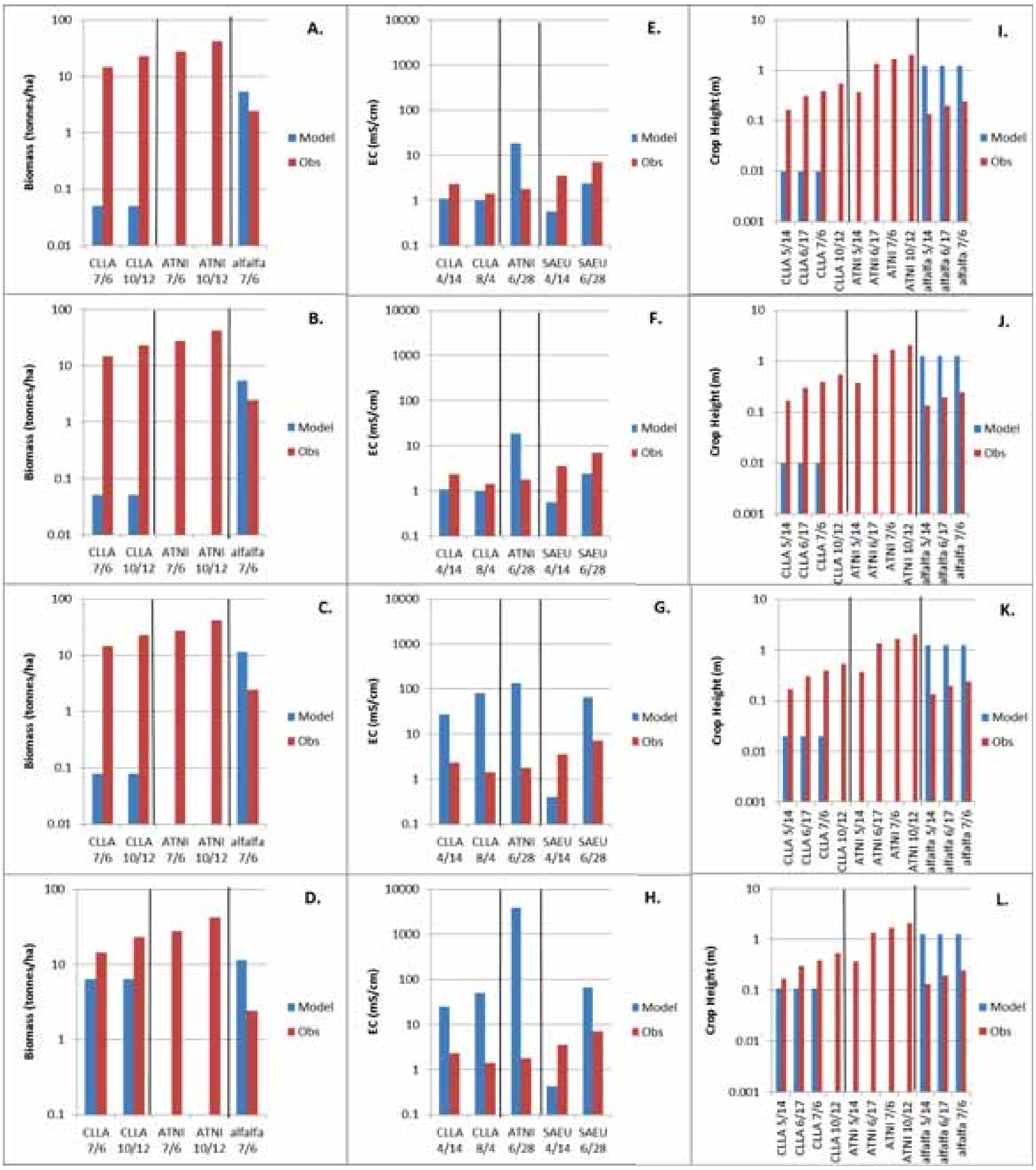

Figure 72: : Kyzylkezek modeled vs observed values for biomass (A. Best RMSE B. Best Soil EC RMSE C. Best Biomass RMSE, D. Best Crop Height RMSE), EC (E. Best RMSE F. Best Soil EC RMSE G. Best Biomass RMSE H. Best Crop Height RMSE), and Crop Height (I. Best RMSE J. Best Soil EC RMSE K. Best Biomass RMSE L. Best Crop Height RMSE)

Appendix H: Calibration Dotty Plots

Below are dotty plots for each sensitive parameter and metric (crop biomass, crop height, soil EC) in Khorezm and Kyzylkezek. These graphs are used to see the relationship between parameter and model performance. Lower RMSE's indicate better model performance.

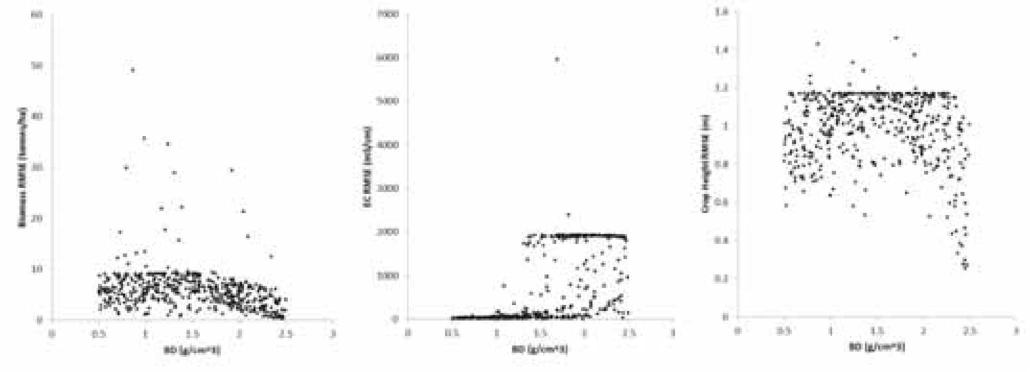

Figure 73: Khorezm, all crops, BD

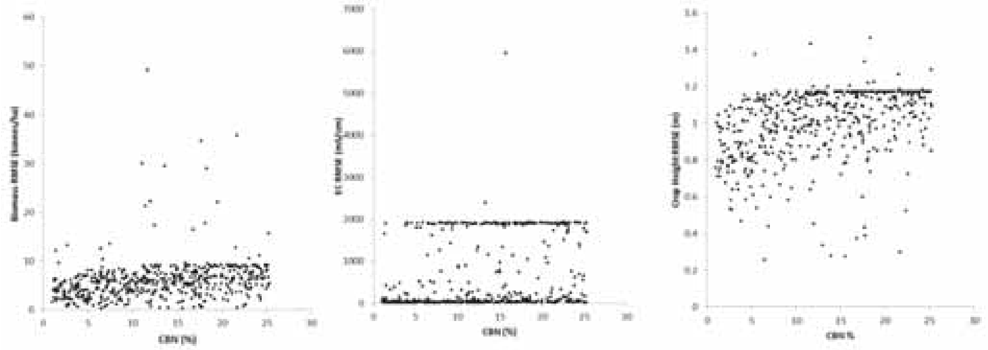

Figure 74: Khorezm, all crops, CBN

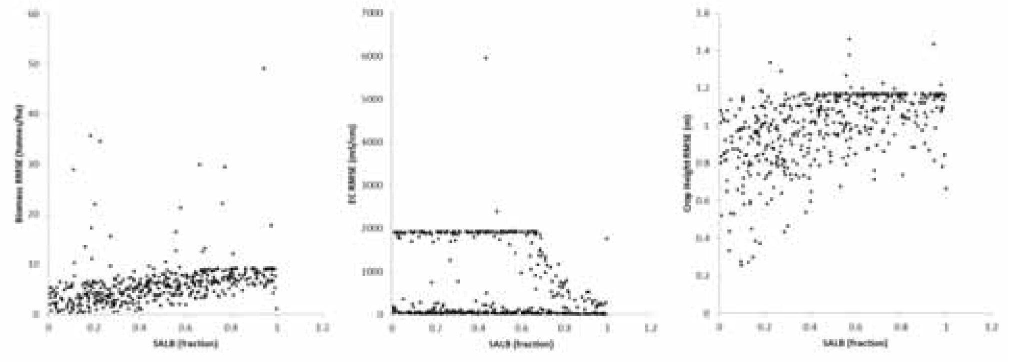

Figure 75: Khorezm, all crops, SALB

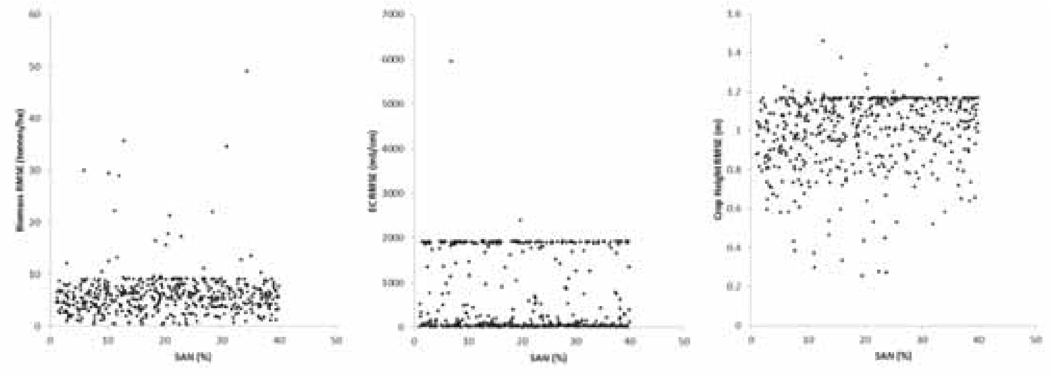

Figure 76: Khorezm, all crops, SAN

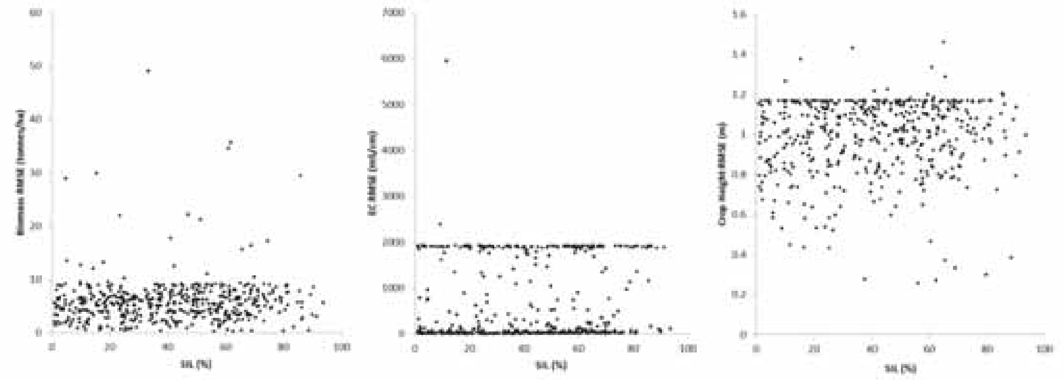

Figure 77: Khorezm, all crops, SIL

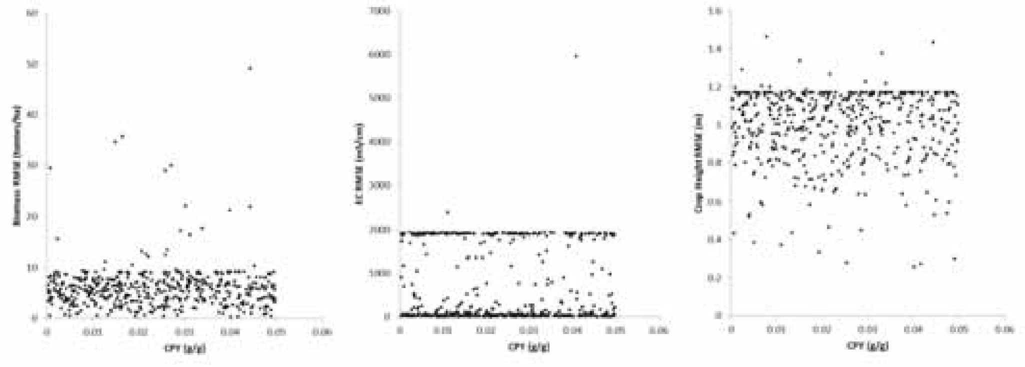

Figure 78: Khorezm, *Atriplex nitens*, CPY

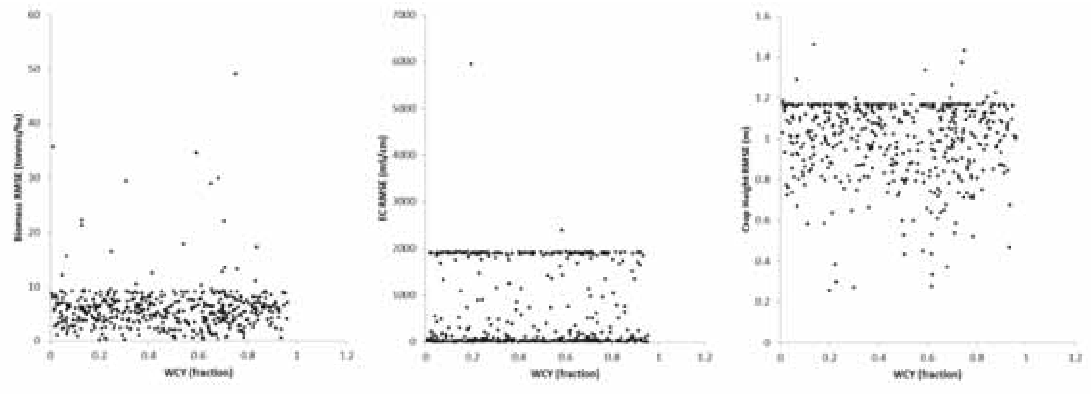

Figure 79: Khorezm, *Atriplex nitens*, WCY

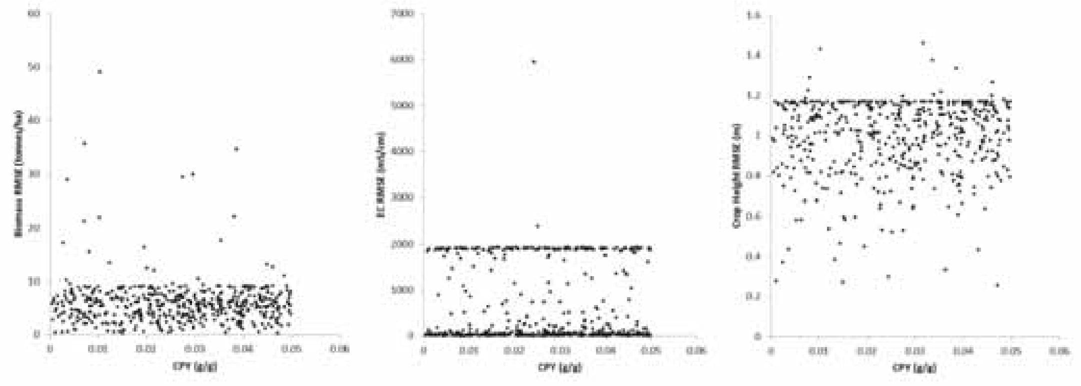

Figure 80: Khorezm, *Climacoptera lanata*, CPY

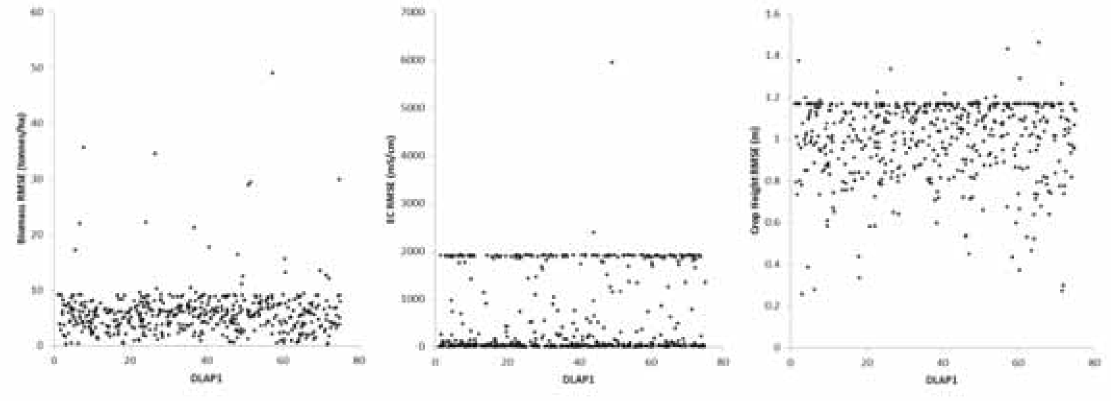

Figure 81: Khorezm, *Climacoptera lanata*, DLAP1

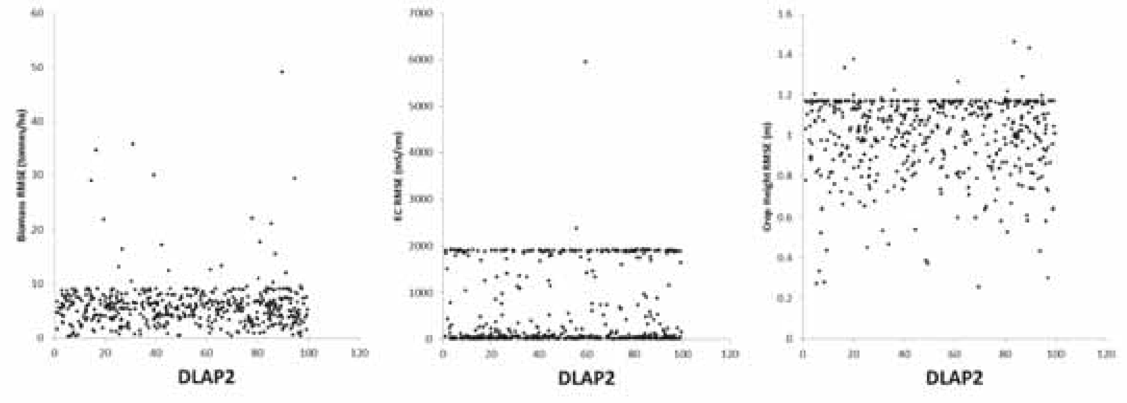

Figure 82: Khorezm, *Climacoptera lanata*, DLAP2

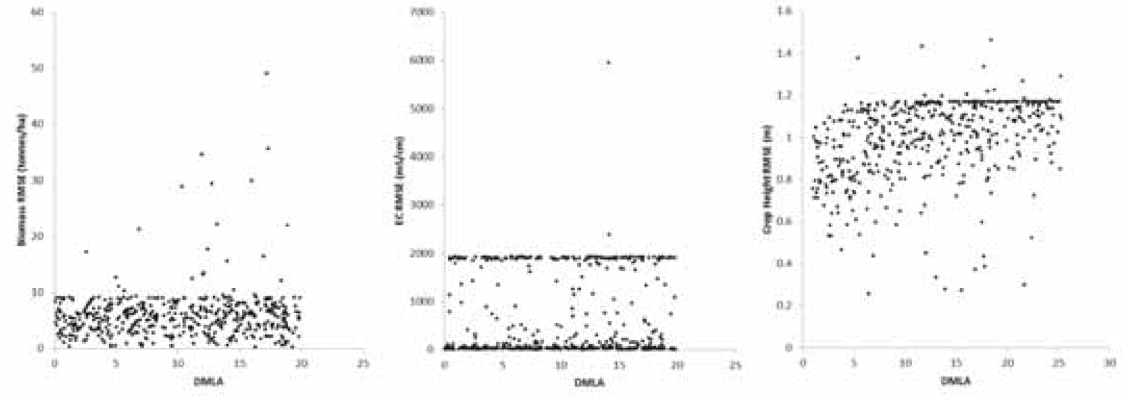

Figure 83: Khorezm, *Climacoptera lanata*, DMLA

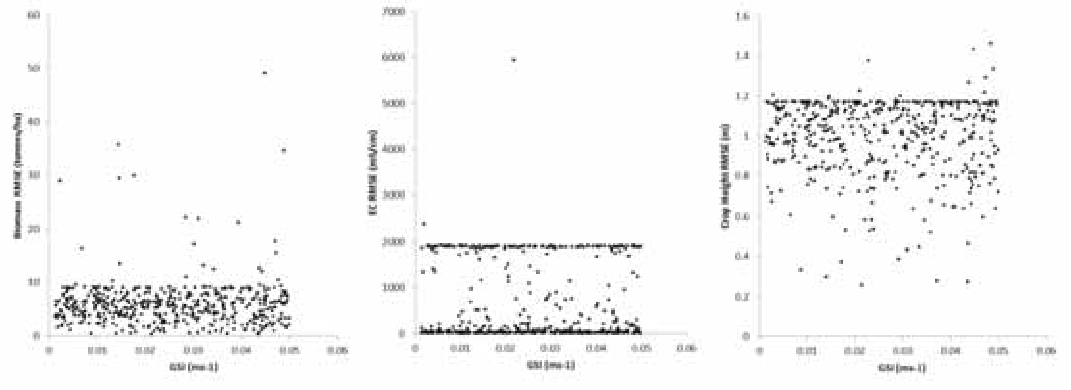

Figure 84: Khorezm, *Climacoptera lanata*, GSI

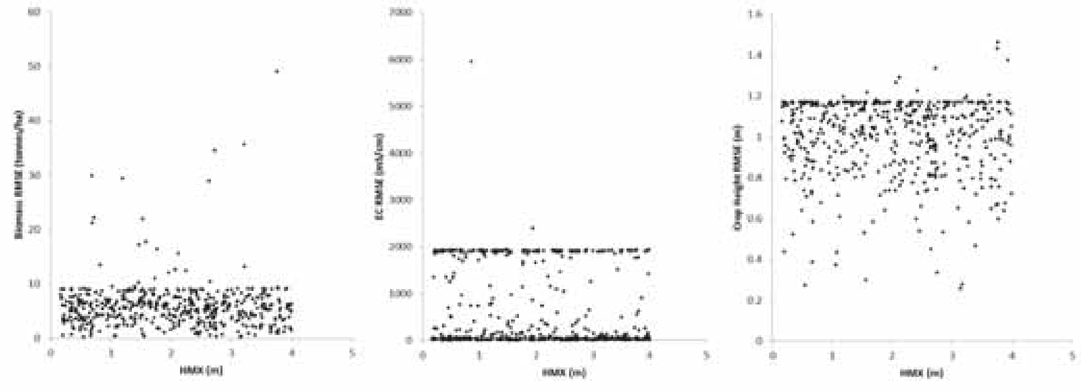

Figure 85: Khorezm, *Climacoptera lanata*, HMX

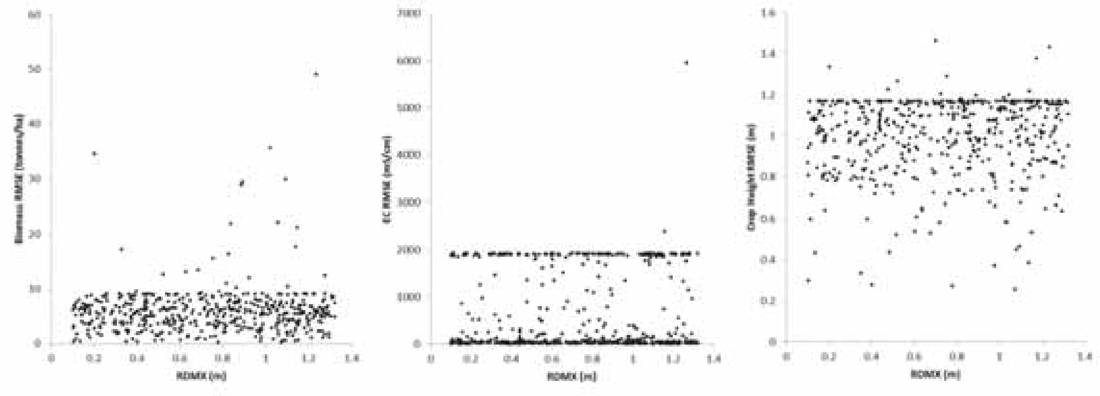

Figure 86: Khorezm, *Climacoptera lanata*, RDMX

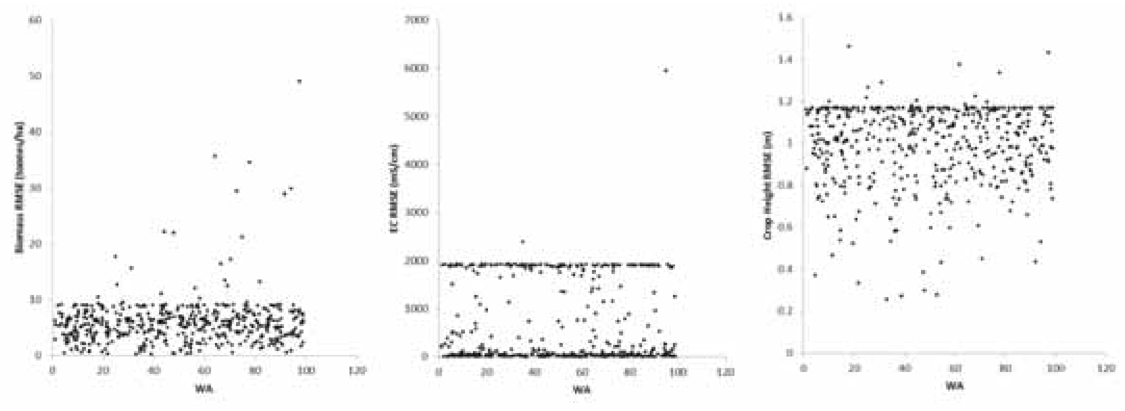

Figure 87: Khorezm, *Climacoptera lanata*, WA

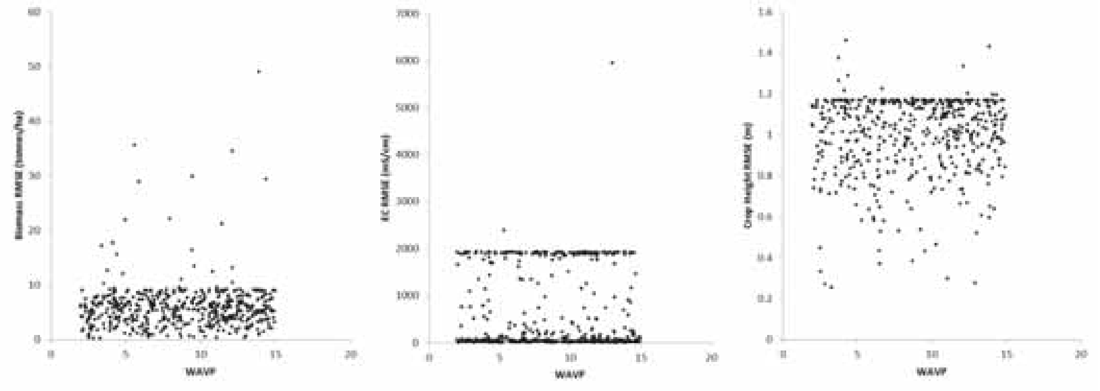

Figure 88: Khorezm, *Climacoptera lanata*, WAVP

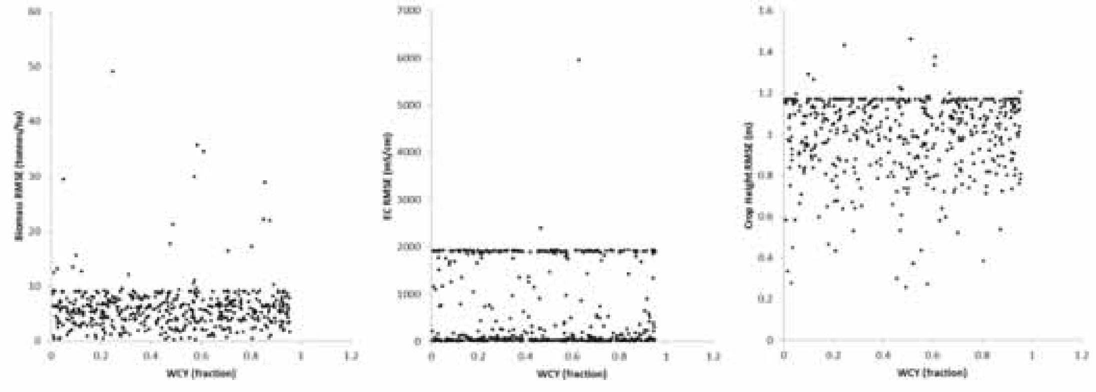

Figure 89: Khorezm, *Climacoptera lanata*, WCY

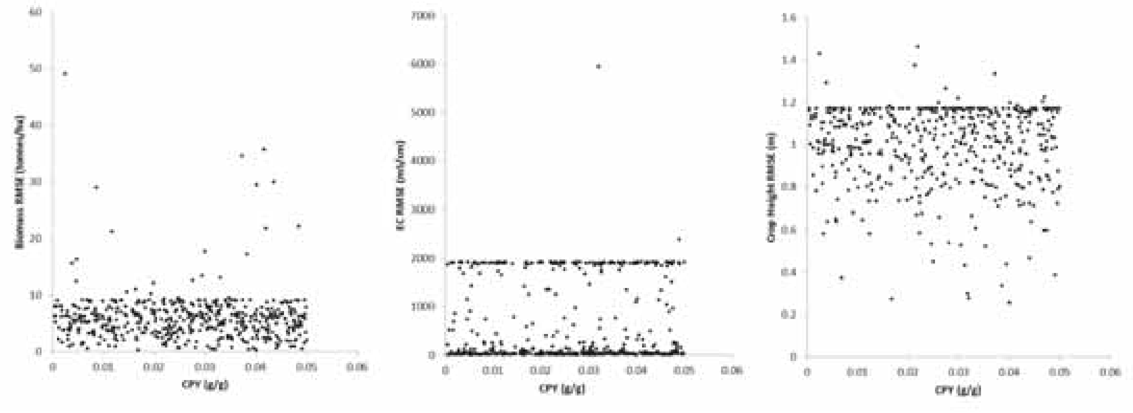

Figure 90: Khorezm, *Salicornia europeae*, CPY

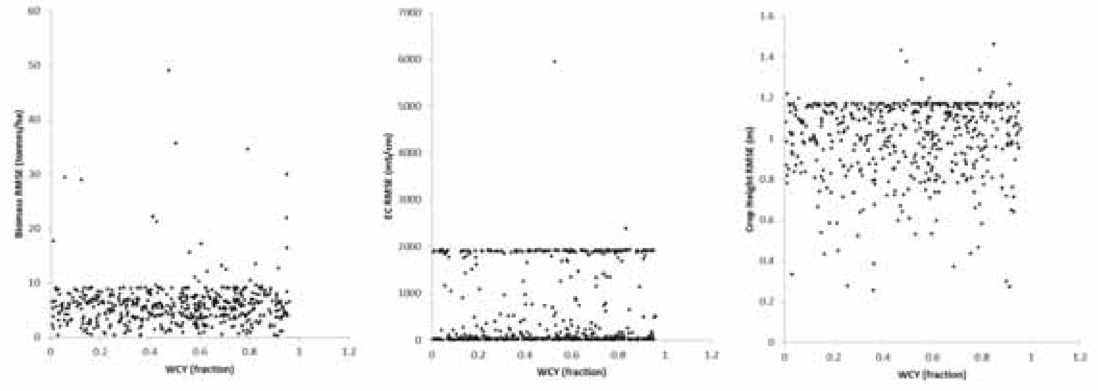

Figure 91: Khorezm, *Salicornia europeae*, WCY

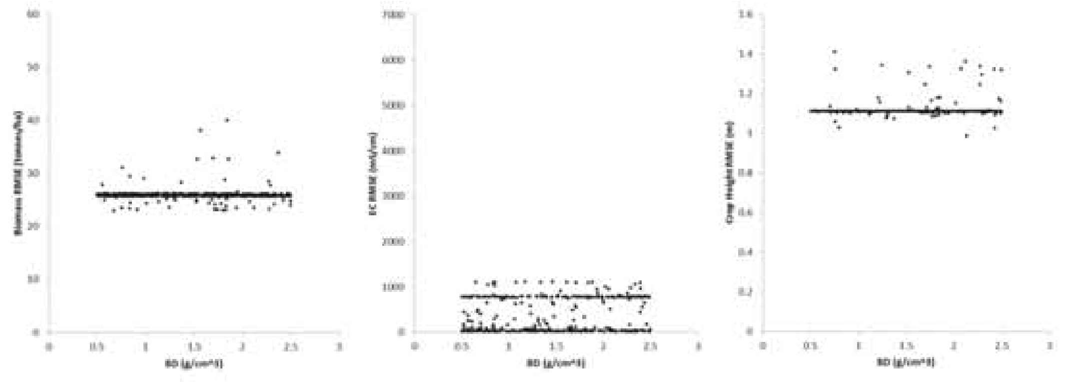

Figure 92: Kyzylkezek, Medicago sativa, BD

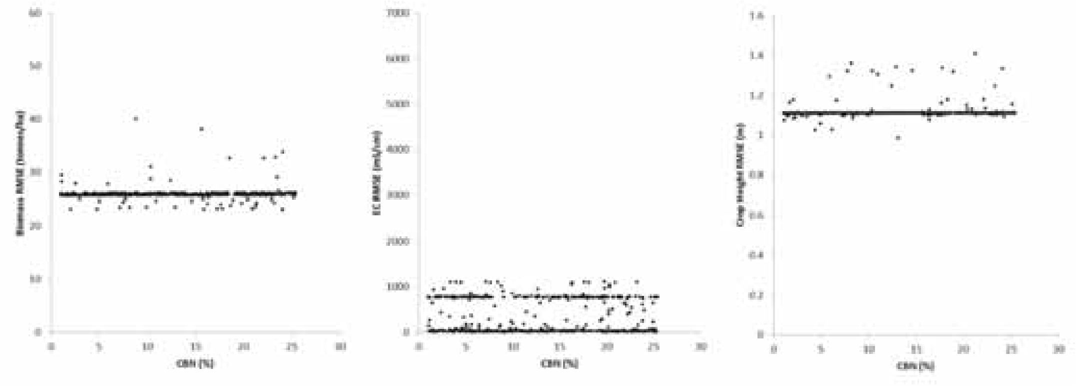

Figure 93: Kyzylkezek, Medicago sativa, CBN

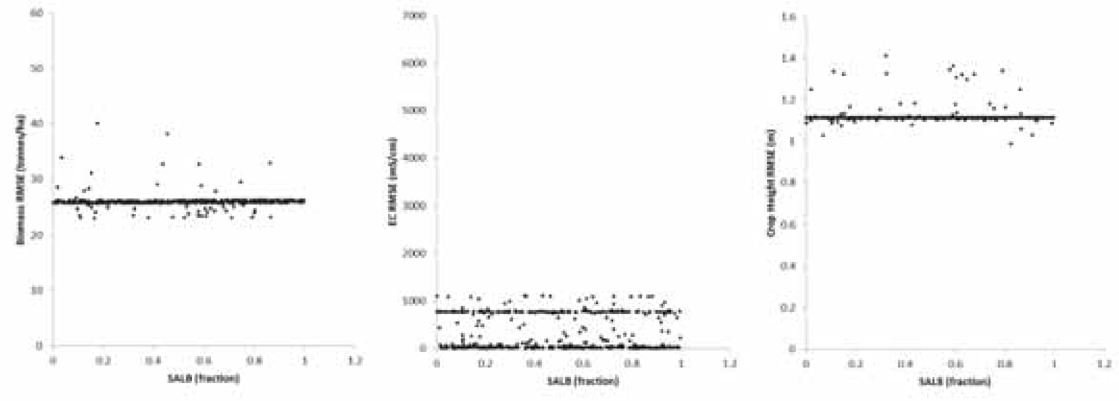

Figure 94: Kyzylkezek, Medicago sativa, SALB

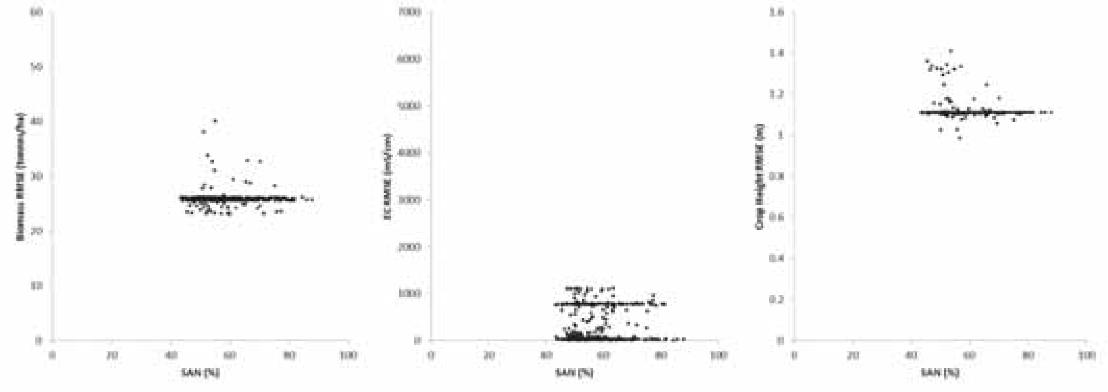

Figure 95: Kyzylkezek, Medicago sativa, SAN

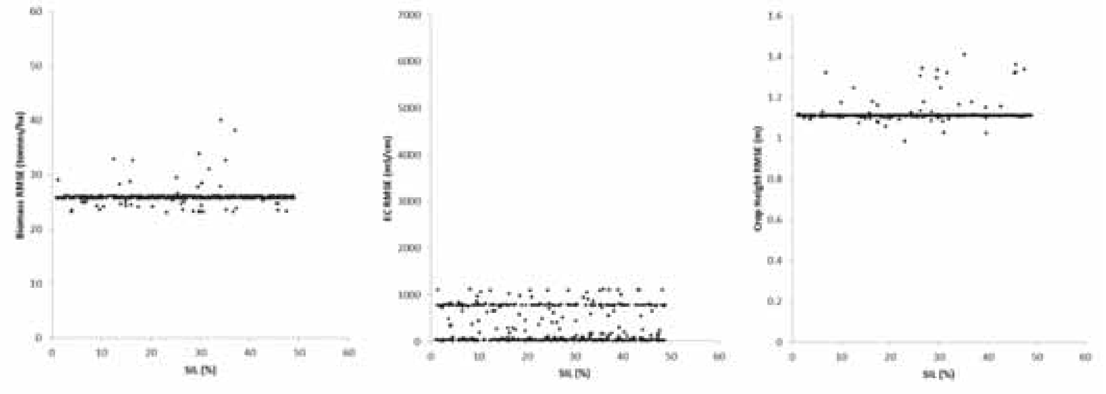

Figure 96: Kyzylkezek, Medicago sativa, SIL

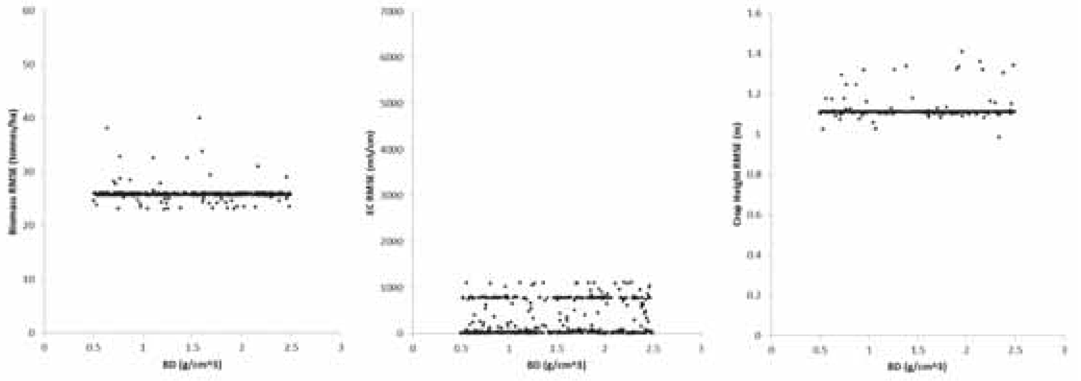

Figure 97: Kyzylkezek, *Atriplex nitens*, BD

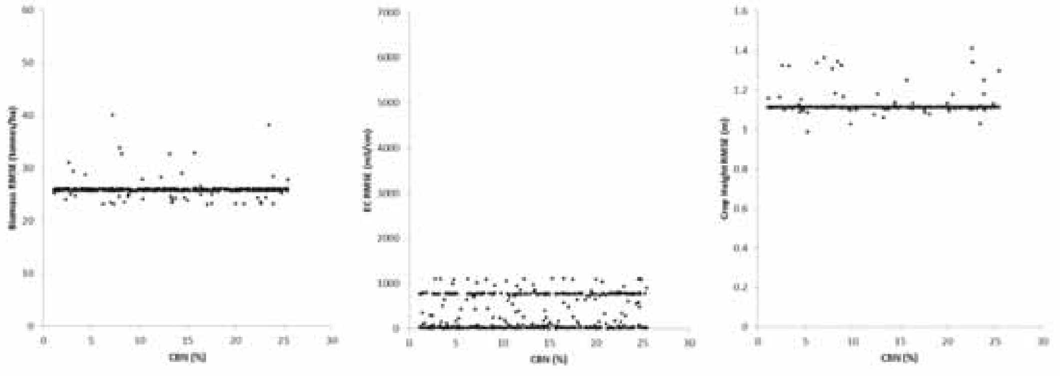

Figure 98: Kyzylkezek, *Atriplex nitens*, CBN

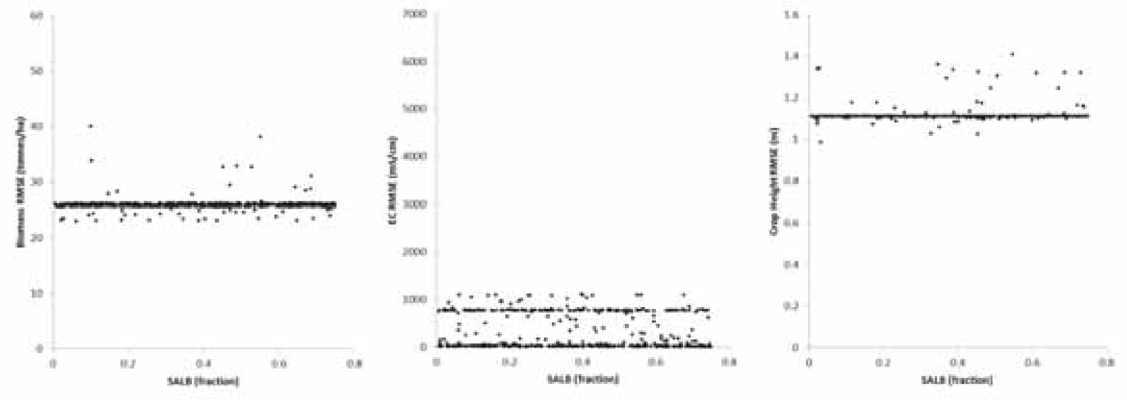

Figure 99: Kyzylkezek, *Atriplex nitens*, SALB

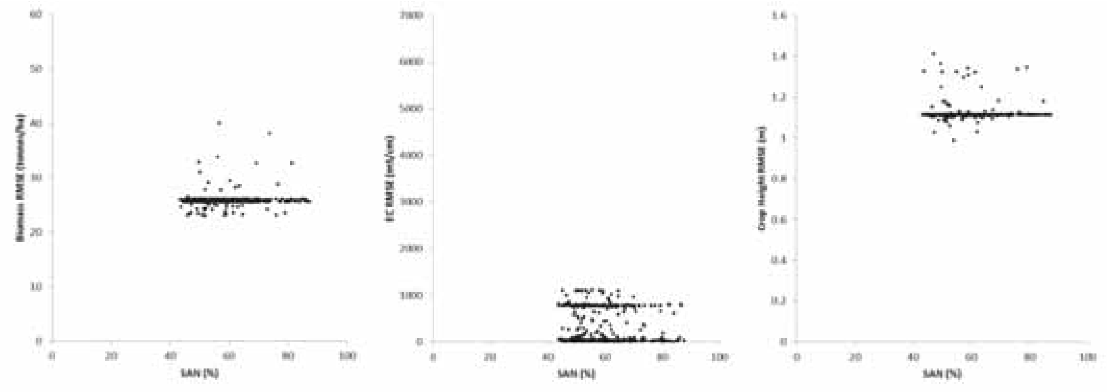

Figure 100: Kyzylkezek, *Atriplex nitens*, SAN

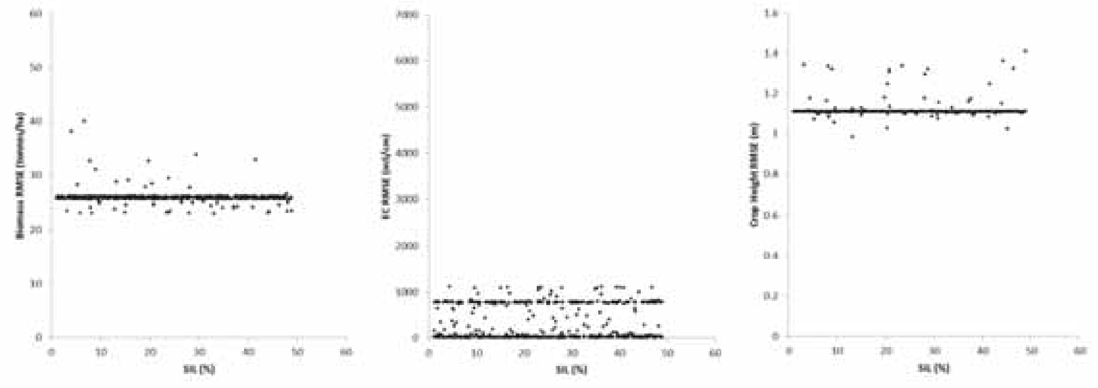

Figure 101: Kyzylkezek, *Atriplex nitens*, SIL

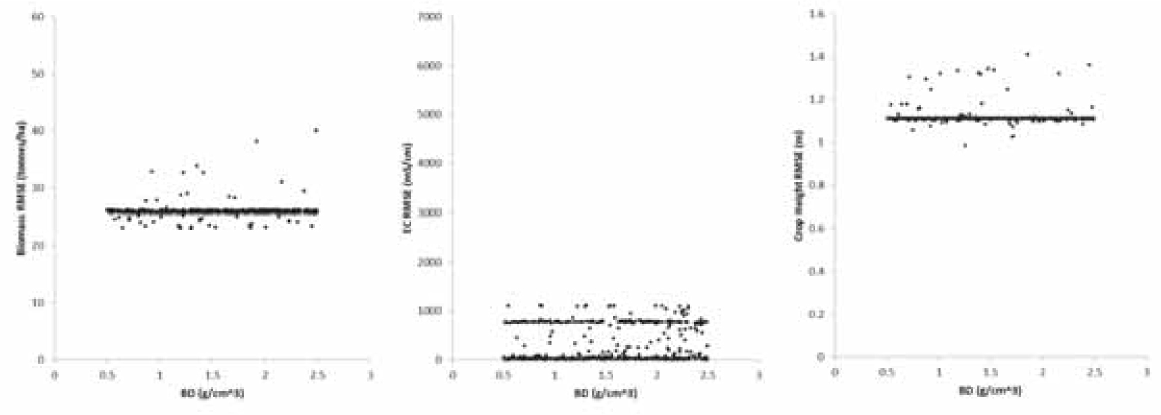

Figure 102: Kyzylkezek, *Climacoptera lanata*, BD

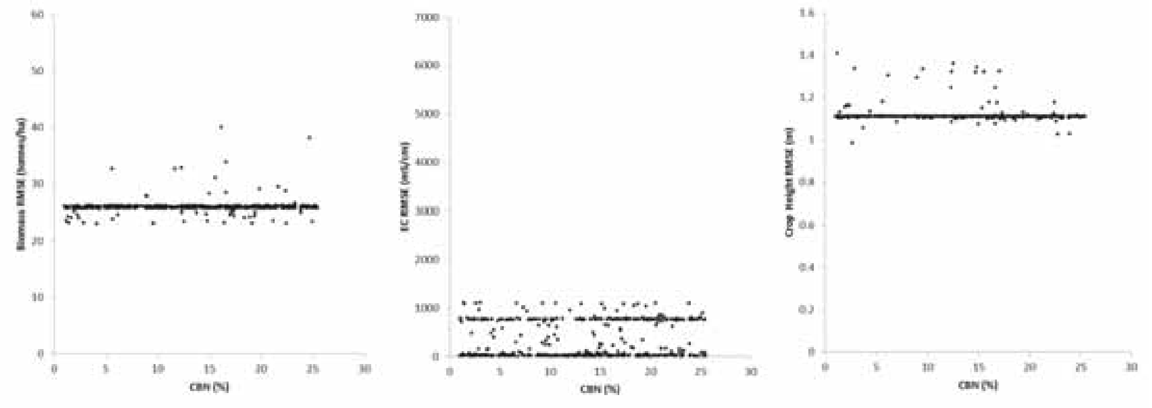

Figure 103: Kyzylkezek, *Climacoptera lanata*, CBN

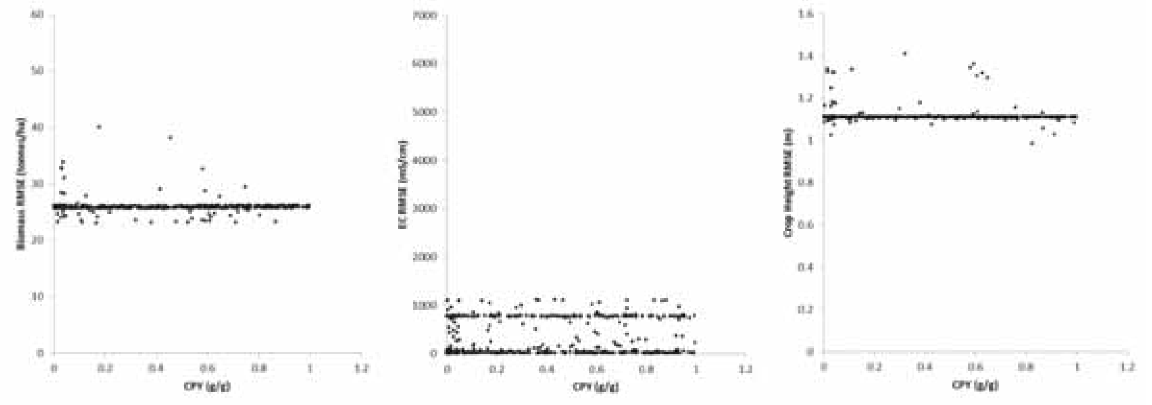

Figure 104: Kyzylkezek, *Climacoptera lanata*, CPY

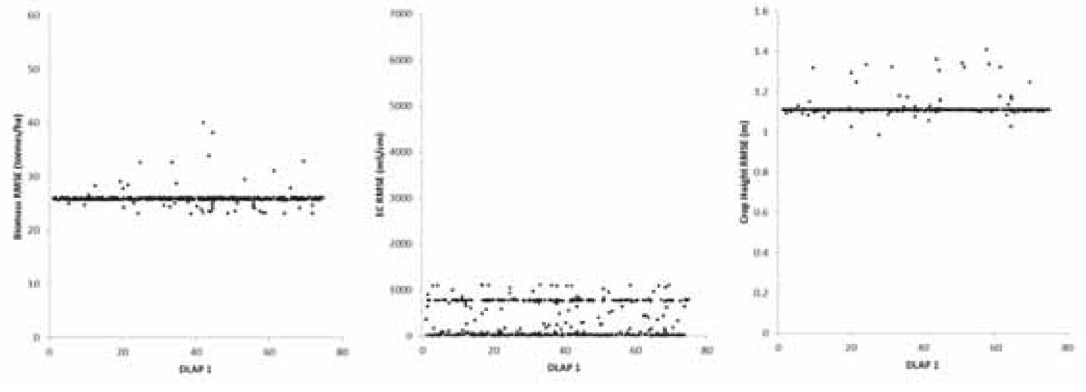

Figure 105: Kyzylkezek, *Climacoptera lanata*, DLAP1

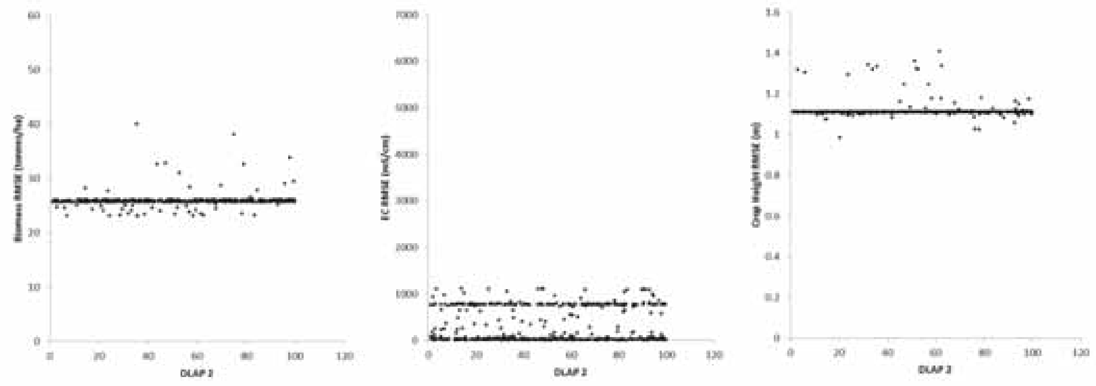

Figure 106: Kyzylkezek, *Climacoptera lanata*, DLAP2

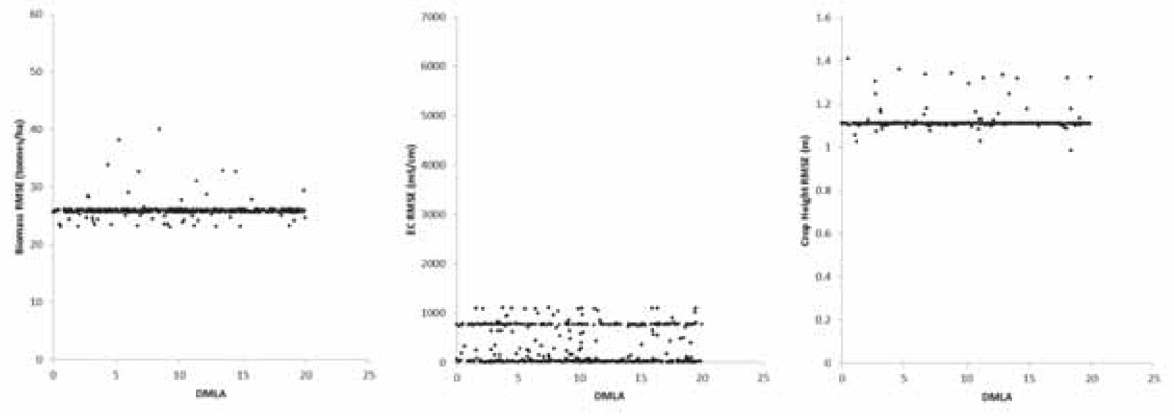

Figure 107: Kyzylkezek, *Climacoptera lanata*, DMLA

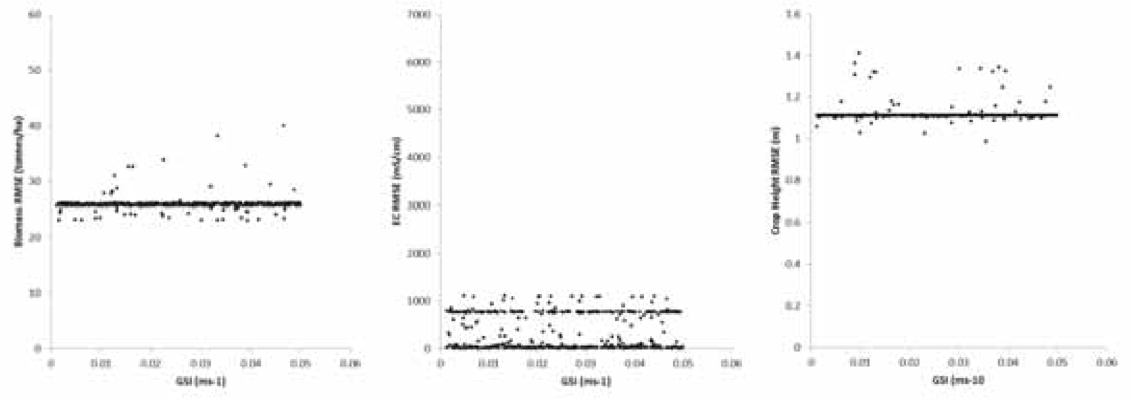

Figure 108: Kyzylkezek, *Climacoptera lanata*, GSI

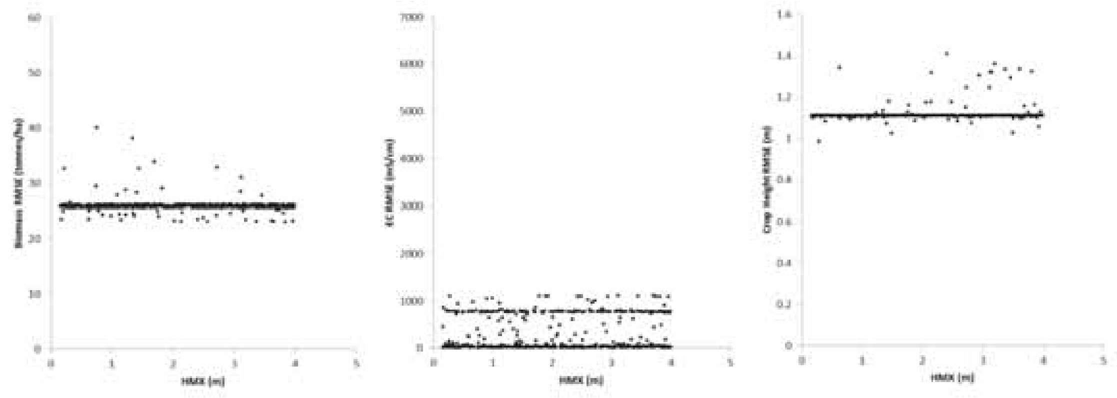

Figure 109: Kyzylkezek, *Climacoptera lanata*, HMX

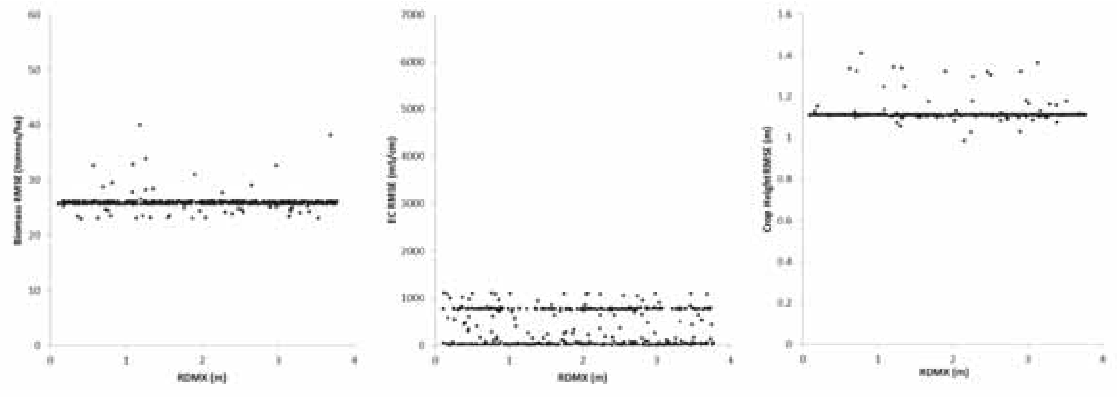

Figure 110: Kyzylkezek, *Climacoptera lanata*, RDMX

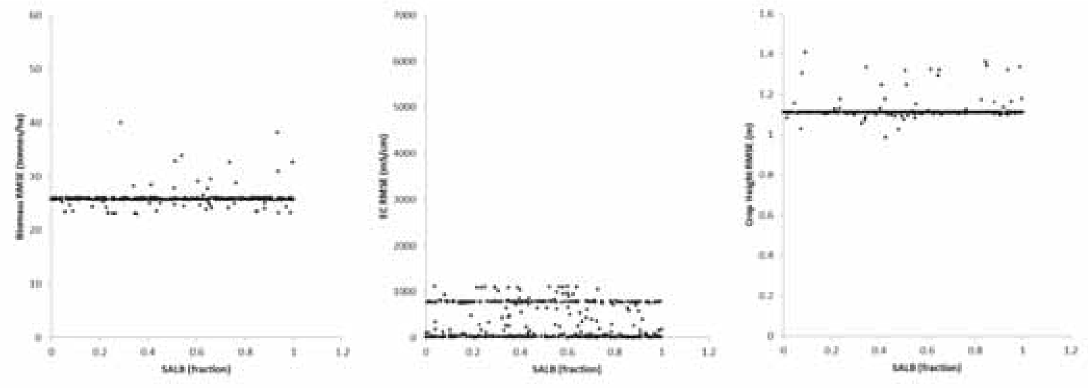

Figure 111: Kyzylkezek, *Climacoptera lanata*, SALB

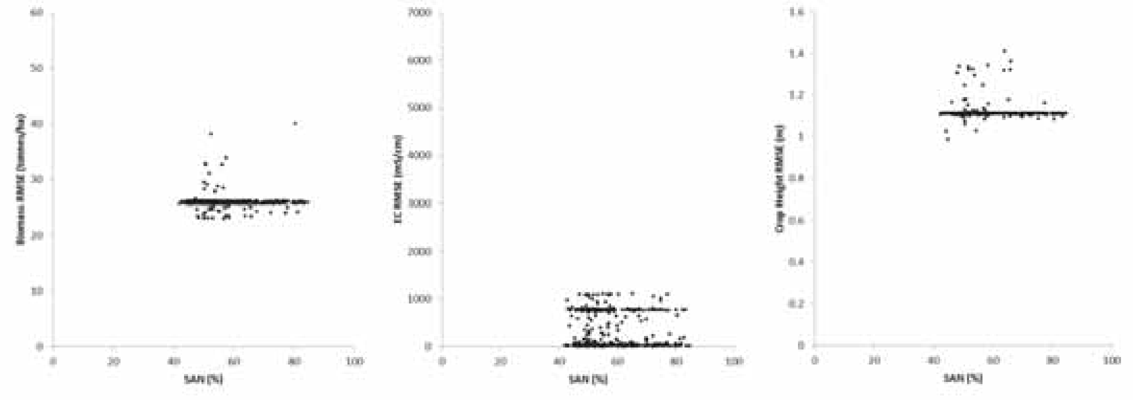

Figure 112: Kyzylkezek, *Climacoptera lanata*, SAN

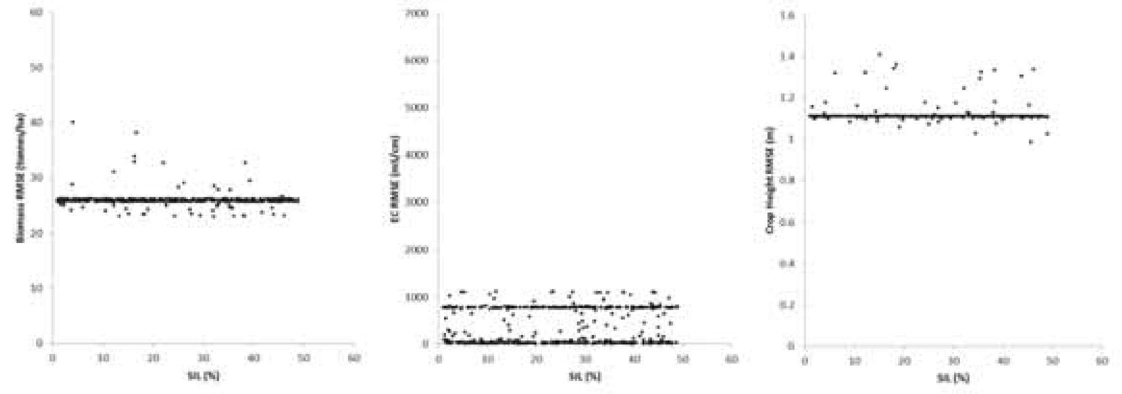

Figure 113: Kyzylkezek, *Climacoptera lanata*, SIL

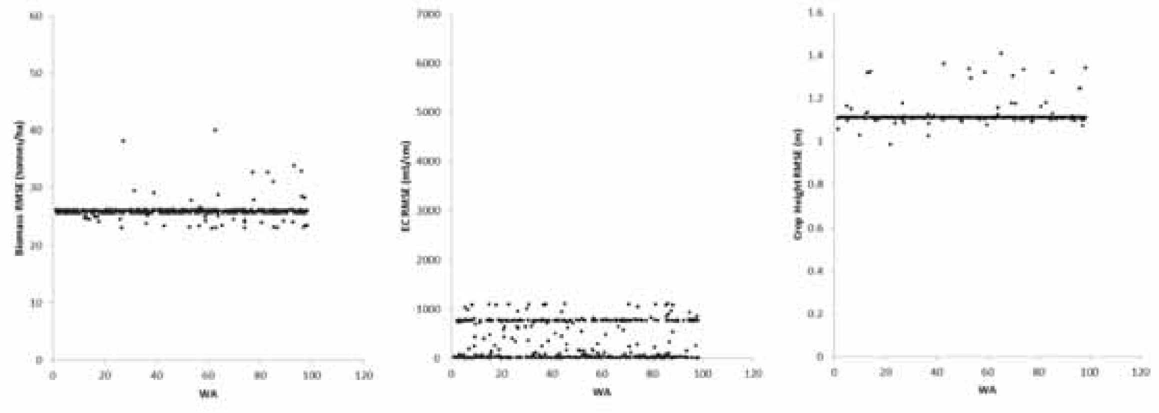

Figure 114: Kyzylkezek, *Climacoptera lanata*, WA

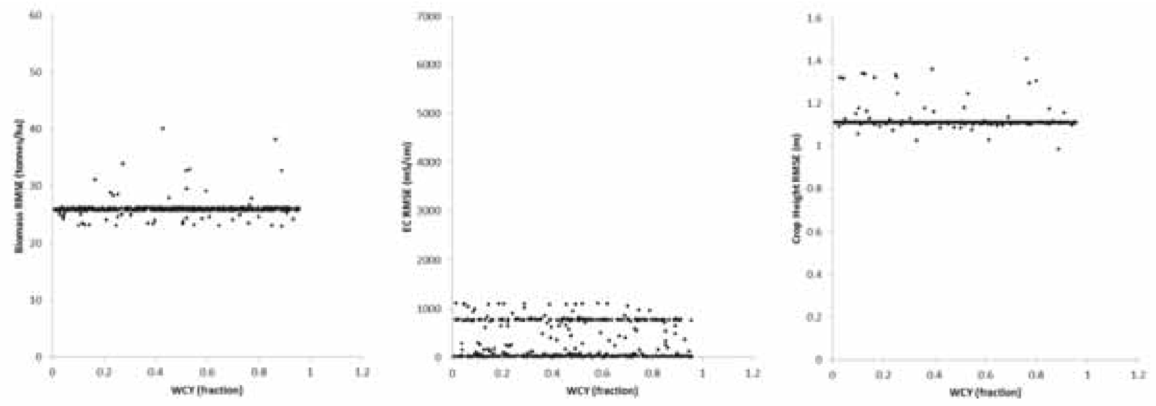

Figure 115: Kyzylkezek, *Climacoptera lanata*, WCY

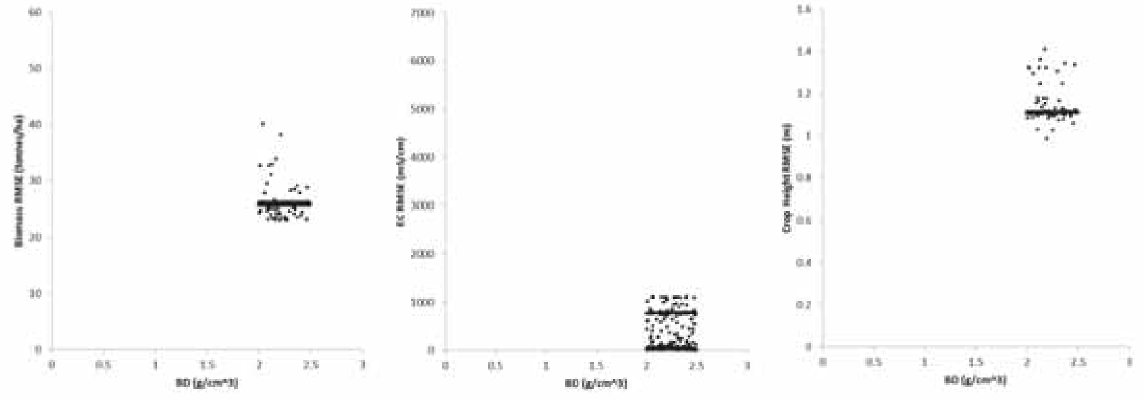

Figure 116: Kyzylkezek, *Salicornia europeae*, BD

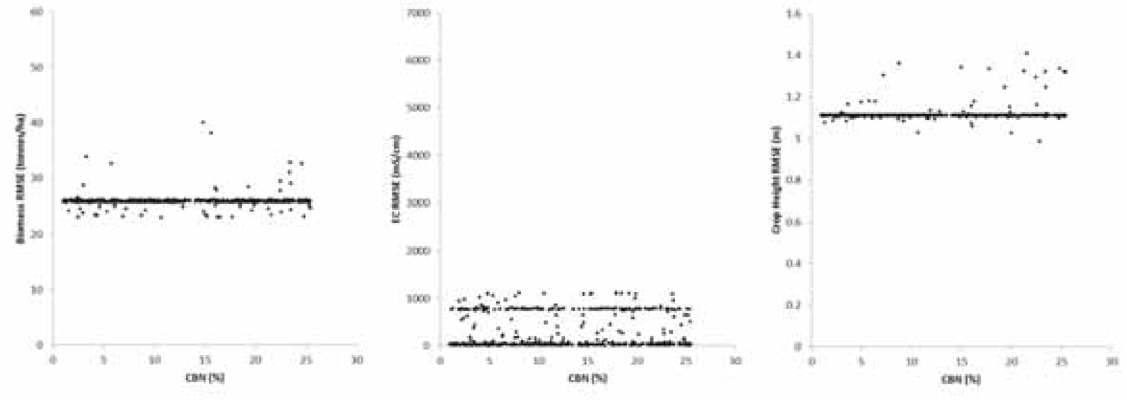

Figure 117: Kyzylkezek, *Salicornia europeae*, CBN

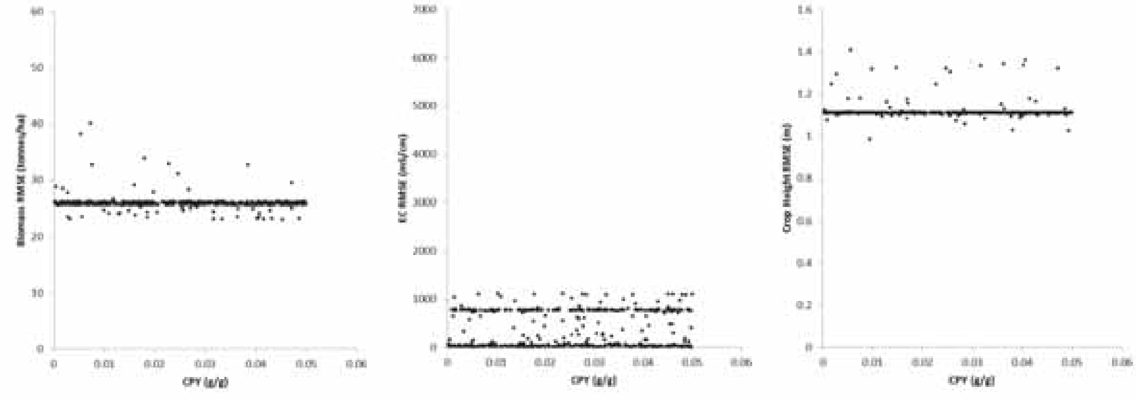

Figure 118: Kyzylkezek, *Salicornia europeae*, CPY

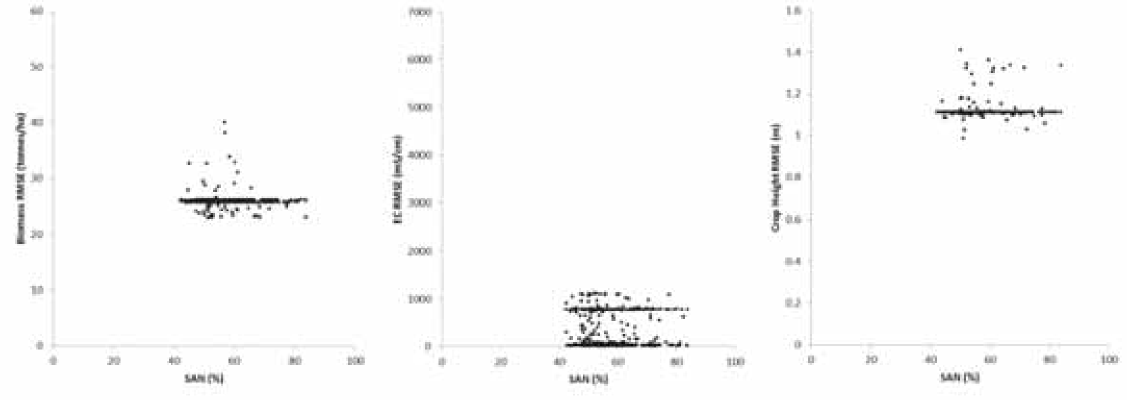

Figure 119: Kyzylkezek, *Salicornia europeae*, SAN

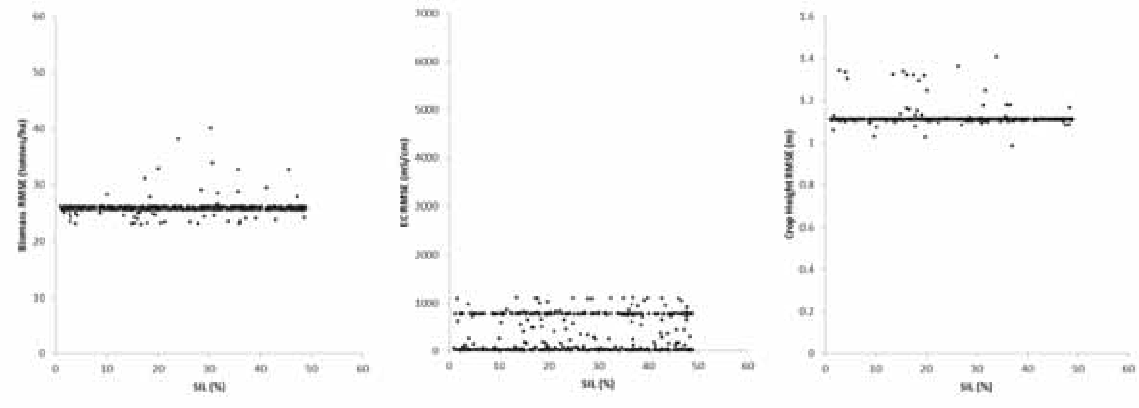

Figure 120: Kyzylkezek, *Salicornia europeae*, SIL

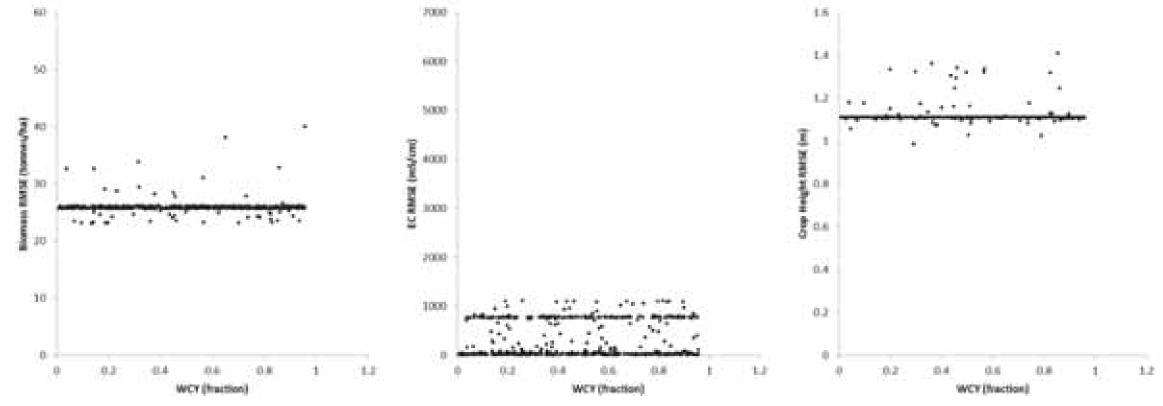

Figure 121: Kyzylkezek, *Salicornia europeae*, WCY

Appendix I: Sodic Soils and Agriculture

This appendix may be helpful for future model development. Salinity modules should reflect the mechanisms of how plants are affected by soil salts.

I.1 Introduction

All irrigation water contains dissolved solids. Calcium (Ca^{2+}), Mg^{2+}, and Na^{+} are the most common cations, and the most common anions are Cl^{-}, SO_4^{2-}, and bicarbonate (HCO_3^{-}). Other ions such as K^{+}, carbonate (CO_3^{2-}), and NO_3^{-} also can be present, but are generally in concentrations much lower than the other more common ions (Lauchli and Grattan 2012).

The reduction in plant yield is a function of how plants deal with salts. Both salinity, or the salt concentration, and sodicity, or the ionic composition of the salt, affect plant yield (Lauchli and Grattan 2012). Salinity and sodicity are distinctly different. Salinity is a direct effect of the salt on the plant: it is the amount of salt in the irrigation water or soil that causes adverse effects to the crop by reducing the osmotic potential of the soil solution or by specific ions, causing specific injury to the crop. Sodicity, however, is the proportion of Na^{+} in the water or adsorbed to the soil surface relative to the amount of Ca^{2+} and Mg^{2+}. Sodicity affects the plants less directly than salinity does. Sodicity can cause nutrient imbalances in the plants or deteriorate the physical properties of the soil, and cause crusting, reduced infiltration, increased soil strength, and reduced aeration causing anoxic or hypoxic conditions for roots (Lauchli and Grattan 2012).

Sodicity is characterized by the percentage of the cation exchange capacity (CEC) occupied by sodium, or the exchangeable sodium percentage (ESP). Sodicity is essentially the proportion of sodium in the water or adsorbed to the soil particles qualified by the amount of calcium and magnesium (Lauchli and Grattan 2012). ESP is generally defined as (Robbins 1984):

$$ESP = \frac{Exchangeable\ Na^{+}}{CEC} * 100\% \tag{11}$$

Sodicity in the water is called the sodium adsorption ratio (SAR), and is calculated by the following equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}} \tag{12}$$

where Na^{+}, Ca^{2+}, and Mg^{2+} are all concentrations of their respective cations in molarities. The ESP and SAR are not equal, but generally have similar values in the range of 3 to 30 (Lauchli and Grattan 2012). The difference can be explained by the empirical equation (Seilsepour et al. 2009):

$$ESP = 1.95 + 1.03 * SAR \tag{13}$$

Typically, soils are considered saline when the electrical conductivity of a saturated soil extract exceeds 4 mS/cm at 25° C and sodic when the ESP exceeds 15%, but these standards can be misleading because of other factors that affect crop responses to salinity such as climate, crop type, soil minerology, clay or organic matter, ionic strength, and the composition of the irrigation water (Lauchli and Grattan 2012).

Sodic soils can be divided into saline-sodic and sodic soils based on their SAR, electrical conductivity (EC). Saline-sodic soil have SAR greater than 3 and an EC greater than a threshold concentration (TC) which is usually 0.4 dS/m. Sodic soils have a SAR greater than 3 as well, but the EC is less than TC. Saline-sodic and sodic soils can have a large impact on plants and the environment (Figure 122), such as reduced plant growth and yield, loss of natural resources, and pollution of heavy metals and nutrients in nearby water bodies. Saline-sodic soils can become sodic soils by leaching salts. Seasonal leaching is practiced by many farmers worldwide to rid their crops of salt. Leaching flushes some of the accumulated salts from the agricultural land, but it also flushes fertilizer, pesticides, and other contaminants into nearby water bodies. Sodic soils can be further broken down into smaller classifications by their pH. Acidic sodic soils have a pH less than 6, neutral sodic soils have a pH between 6 and 8, and alkaline sodic soils have a pH greater than 8. Alkaline sodic soils can cause a further toxicity or deficiency of micro and macro-nutrient ions (Naidu and Rengasamy 1993).

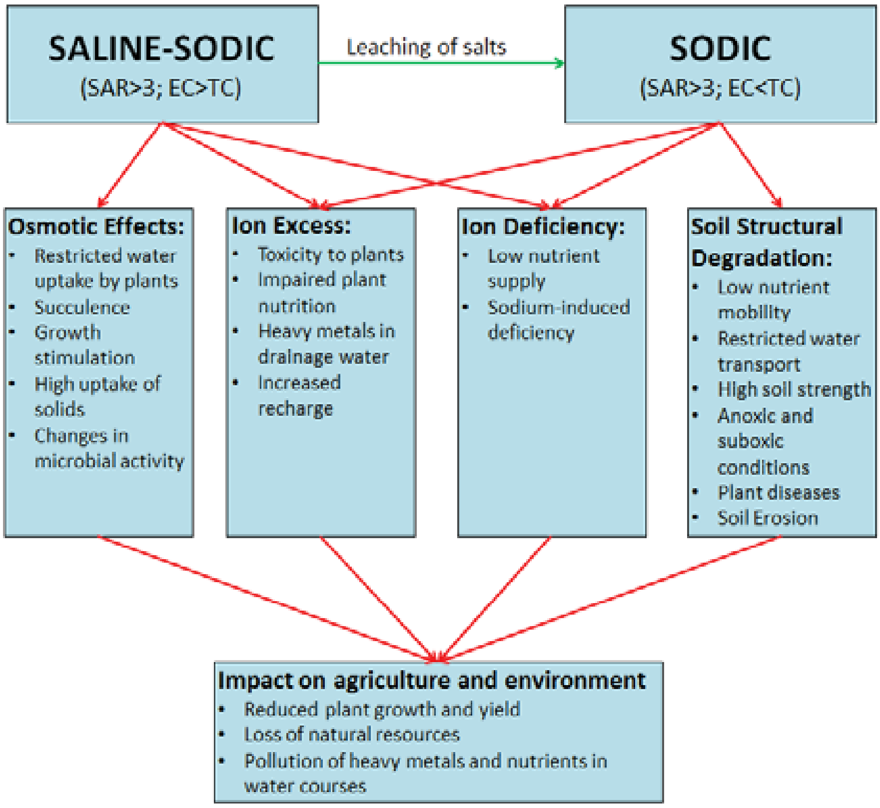

Figure 122: Effects of saline-sodic and sodic soils on plants and environment. Adapted from Naidu and Rengasamy (1993)

I.2 Chemistry of Salt-Affected Soils

I.2.1 Crusting and Hydraulic Conductivity

Sodicity can also affect the hydraulic conductivity of a soil. This is largely due to the formation of soil crusts that can reduce infiltration and increase runoff (USDA 1996). Soil crusts are thin, dense, and continuous layers of non-aggregated soil particles on the surface of exposed soils. Crusting is generally less than 2 inches thick but can be expansive (USDA 1996). Crusts can be created when a soil surface dries after rainfall or irrigation. Soil crusts form when water droplets hit the soil aggregates, breaking them into soil particles. The fine soil particles, often clay particles, then settle into the surface pores, creating a seal that can block water from penetrating into the soil. In saline environments, crusts can also be formed by the precipitated salt at the surface that comes into the system often through irrigation (USDA 1996).

Soil crusting itself can restrict seedling emergence depending on the thickness and strength of the crust, the size of the broken crust pieces, the soil water content, and the type of plant species (USDA 1996). Crusts can also reduce oxygen diffusion to the seedlings, especially if the crust is wet. A saline crust may impact germination rates of plants even more because of high salinity. Crusting can also reduce surface water evaporation due to the higher reflectance of crusted soil versus unaffected soil. That results in a cooler soil surface and a lower rate of evaporation (USDA 1996).

The soil crust reduces infiltration rates because it limits the ability of water to penetrate through the crust. The seal formation created by the soil crust as well as infiltration from irrigation or rain are influenced by the ESP and the electrolyte concentration and composition of the water.

Mamedov et al. (2001) studied the relationship between the ESP and seal formation with varying wetting rates on different types of soil. The clay content in the soils ranged from 8.8 to 68.3% and the ESP values ranged from 0.9 to 20.4. The study found that the wetting rate had little effect on seal formation in low-clay soils (8.8% clay), but a large effect in high-clay soils (>52.1% clay). In contrast, the soil ESP relationship to seal formation was a large factor in seal formation for low-clay soils, and a small factor for high-clay soils. Intermediate clay content soils (22.5-40.2% clay) were found to be the most susceptible to seal formation.

I.2.2 Waterlogging and Redox Effects

Subsoil waterlogging is a problem in arable soils with high SAR and pH. When the soil pores are saturated for a long time, carbon dioxide from biological sources builds up, and oxygen depletion occurs. The change in partial pressures of CO_2 and O_2 can cause nutrient ions in soil solutions to undergo chemical transformations. The major chemical elements that are transformed into various species in suboxic and anoxic pE-pH ranges are Fe, Mn, N, O, S, and C (Table 51). In anoxic conditions, anaerobes produce Mn^{2+}, Fe^{2+}, N_2, and S^{2-} species by electron transfer from Mn^{4+}, Fe^{3+}, NO^{3-}, and SO_4^{2-}. This reaction could increase nutrient availability to plants (Appelo and Postma 2010). Though ions such as Zn^{2+}, Co^{2+}, Cu^{2+}, Fe^{2+}, and MoO_4^{2-} are more soluble in poorly drained soils, the pH effect is dominant in alkaline sodic soils and the hydrolyzed species of these ions precipitate. Nutrient deficiencies are caused when hydroxyl species form inner-sphere complexes with aluminol, silanol, or siloxane surfaces of poorly ordered minerals. Heavy metal ions are solubilized by chelation of simple organic molecules that come from anaerobic decomposition of organic matter, but they are unavailable to plants because the pH+pE domains in alkaline sodic soils cause the heavy metals to complex with soil surfaces.

Table 51: pE at pH 7.0 for equilibrium chemical reactions under anoxic and suboxic conditions in sodic soils (Naidu and Rengasamy 1993).

Chemical Reactions			pE
O_2 +4H^+ +4e^-	=	2H_2O	13.80
2NO_3^-+12H^+ +10e^-	=	N_2 + 6H_2O	12.66
MnO_2 + 4H^+ +2e^-	=	Mn2+ +2H_2O	6.80
Fe(OH)$_3$ + 3H^+ +e^-	=	Fe^{2+} + 3H_2O	-3.13
SO_4^{2-} + 10H^+ +8e^-	=	H_2S + 4H_2O	-3.63
CO_2 + 8H^+ +8e^-	=	CH_4 + 2H_2O	-4.14
N2 + 8H+ + 6e-	=	2NH_4^+	-4.69
2H^+ + 2e^-	=	H_2	-7.00

Denitrification processes in waterlogged soils can also occur. Nitrogen losses are high when alternating oxic and anoxic conditions occur. This pattern occurs in sodic soils that are seasonally waterlogged. Low concentrations of N can occur in high pH sodic-soils and be ploblematic for agriculture because N can be lost as NH_3 gas or precipitated as $(NH_4)_2CO_3$ (Appelo and Postma 2010).

Phosphorous availability is generally increased in waterlogged soils because of the reduced conditions. The reduction of ferric phosphates and dissolution of other phosphates frees the phosphate to be available to the plants (Appelo and Postma 2010). Exchangeable sodium also can increase the concentration of soluble P by enhancing the dissociation of organic ions which then can exchange phosphate anions from Al and Fe complexes. Sodium replaces Ca^{2+}, Mg^{2+}, and Al^{3+} on exchange sites, which causes an increased surface negative potential. Negative surface potential leads to P desorption (Appelo and Postma 2010).

I.2.3 Remediation

Remediation techniques are often necessary to make the soil temporarily suitable for crop production. Remediation techniques involve reducing the ESP, pH, and SAR while increasing the solubilization of calcite ($CaCO_3$) to a point that conditions are physiochemically suitable for plant growth. Salt-affected soils can be temporarily remediated through several methods (Singh et al. 2013). Chemical amendments such as gypsum ($CaSO_4$) can provide enough Ca^{2+} to replace the excess Na^+ from the cation exchange complex (Singh et al. 2013). Gypsum can slightly increase the soil salinity which reduces swelling (New South Wales Department of Primary Industries 1995).

The exchange process requires that Na^+ is removed from the colloid’s cation exchange sites by gypsum. Exchange sites are important in reclamation because of the toxicity of Na^+ and also because soil can exhibit structural problems caused by low infiltration when the adsorbed sodium occupies as few as 6% of the exchange sites (Appelo and Postma 2005). The adsorption of sodium is important to understand when looking at how plants respond to saline soils.

When diluted, divalent ions are preferentially adsorbed compared to monovalent ions. A common exchange reaction is between Ca^{2+} and Na^+ (Appelo and Postma 2005):

$$\tfrac{1}{2}\,Ca^{2+} + Na\text{-}X \longleftrightarrow \tfrac{1}{2}\,Ca\text{-}X_2 + Na^{+} \qquad (14)$$

The law of mass action would then yield:

$$\frac{[Na^{+}]}{[Ca^{2+}]^{0.5}} = \frac{[Na-X]}{[Ca-X2]} \qquad (15)$$

This relationship means that the divalent cation (in this case Ca^{2+}) would have to be diluted ten times more than the monovalent cation (in this case Na^{+}) in order to maintain equilibrium with the exchangeable activities (Appelo and Postma 2005).

The process of exchanging sodium with calcium depends on water leaching the replaced sodium out of the root zone through the percolating water (Ilyas et al. 1997). The effectiveness of this remediation technique depends on the permeability of the soil. Gypsum applications tend to increase permeability and leaching, and improve flocculation and macroporosity, and reduce bulk density and surface crusting, but the effects are often restricted to shallow depths (Ilyas et al. 1997).

I.3 Soil Effects on Plants

I.3.1 Nutrients

When agricultural land is not fertilized, nutrient ions that are necessary for plant growth must be taken from weathering products of primary minerals and clay minerals, and the breakdown of organic matter. Many processes can affect the nutrient ion concentrations such as climate and soil management practices (i.e. added lime, gypsum, and organic matter, tillage, and irrigation) (Naidu and Rengasamy 1993). Mechanisms such as ion exchange, solution and precipitation, ion-pair formation, specific adsorption, and microbial assimilation can all affect nutrient ion concentrations in sodic soils (Table 52). Ion-pairs are created when anions such as sulfate and carbonate associated with multivalent cations. These ion-pairs result in reduced activity of ionic species and low availability of nutrient ions such as calcium and magnesium (Naidu and Rengasamy 1993). Ion-pair formation can also reduce the activity of toxic ion species such as Al^{3+}. In sodic soils, carbonate, bicarbonate, and sulfate ion-pairs reduce divalent ion activity which affects the apparent ‘activity’ SAR (Naidu and Rengasamy 1993). ‘Activity’ SAR is the SAR determined by the activities of the cations whereas ‘practical’ SAR is determined by the anion concentrations.

Table 52: Table of the factors that affect nutrient ion concentrations in sodic soils. Adapted from Naidu and Rengasamy (1993)

Mechanism	Soil Conditions	Effect
Ion exchange	Suite and amount of clay minerals and amorphous componds	Control charge density, exchange selectivity coefficient, and pH-dependent charge
	Organic matter	
	Leaching	
Solution and Precipitation	Partial Pressure of CO_2	Affects pH, solution and precipitation of carbonates and bicarbonates and ion activities
	Organic matter	Controls the release of ions from humified materials, ligand exchange, chelation, and pH-pE relationships
	Soil pH	Primary factor in mineral dissolution
	Waterlogging	Alters soil pH and pE, pH and pE relations affecting the nature of chemical species
Ion-pair formation	Excess anions	High proportions of SO_4^{2-}, CO_3^{2-}, and HCO_3^- result in ion-pair formation and reduce ion activity
Specific adsorption	Surface area and charge	Affects inner-sphere surface complexes and molecular adsorption
	Soil pH	Controls hydrolysis reactions of metal cations and the stability of metal-organic complexes
	Organic molecules	Affects metal-ligand complexation and chelation
Microbial assimilation and excretion	Plant roots	Control microbial activity
	Organic matter	Controls anaerobic or aerobic conditions for microbial reactions
	Drainage	

Organic matter is important to nutrient availability in the soil because it supplies important nutrients such as nitrogen to the plants. The storage and release of nutrients such as Nitrogen, Phosphorous, and Sulfur are controlled by biological processes whereas chemical processes control macro and micro-nutrient cation interactions (Appelo and Postma 2005). The majority of N and S in agricultural solids are found in organic matter. Between 20 and 75% of the P in surface soils is also found in soil organic matter. Organic matter accumulation in sodic soils is affected by Na^+ because Na-organic complexes tend to be highly soluble and therefore highly mobile. Additionally, N mineralization decreases in soils with high SAR. Generally, the ability of cations to fuel organic N mineralization decreases with ionic potential ($Al^{3+} > Fe^{3+} > Ca^{2+} > Mg^{2+} > K^+$

>Na^+), meaning that when SAR is increased in sodic soils, organic matter has a decreasing nutrient contribution (Appelo and Postma 2005).

I.3.2 Ion Toxicity and Nutrient Deficiency

The predominate ions in many saline soils, particularly those that are saline because of anthropogenic activity, are Na^+ and Cl^-. High concentrations of Na^+ can affect plant growth besides the osmotic effects caused by elevated EC (Naidu and Rengasamy 1993). High concentrations of Na^+ can be toxic to plants depending on their genetic capabilities for coping with salts. When the Ca^{2+} concentration is low compared to that of Na^+, the Na/Ca ratio becomes high, leading to nutritional imbalances and adverse physiological effects on plants. The high uptake of Na^+ and low uptake of Ca^{2+} by plants in sodic soils affects membrane permeability and the stability of the plant. This instability reduces the transport of other nutrient ions. Low Ca^{2+} concentrations can also cause increased uptake of toxic elements such as Zn, Ni, Mg, Pb, Se, Al, and B (Naidu and Rengasamy 1993).

Saline-sodic soils suffer from ion excess, whereas sodic soils suffer from ion deficiency. Both saline-sodic and sodic soils can have sodium induced ion toxicity and deficiency. Ion deficiency and sodium induced toxicity is exacerbated with increasing pH (Figure 123; Naidu and Rengasamy 1993).

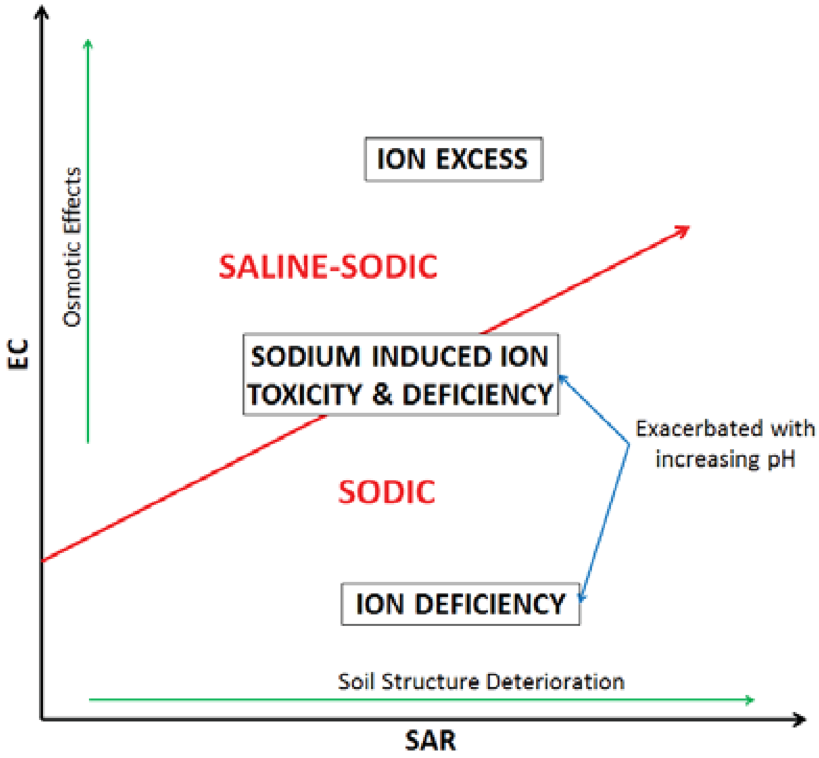

Figure 123: Mechanisms of nutrient constraints in saline-sodic and sodic soils and how they are affected by EC and SAR. Adapted from Naidu and Rengasamy (1993).

I.3.3 Osmotic Potential

One of the ways that plants are adversely affected by saline soils is the osmotic effect in which high salt concentrations outside of the plant reduce the soil water osmotic potential. Plants subjected to this kind of stress must exert energy to reverse the osmosis process and draw water into their cells. This energy would otherwise go toward other vital processes such as plant growth (Munns 2005).