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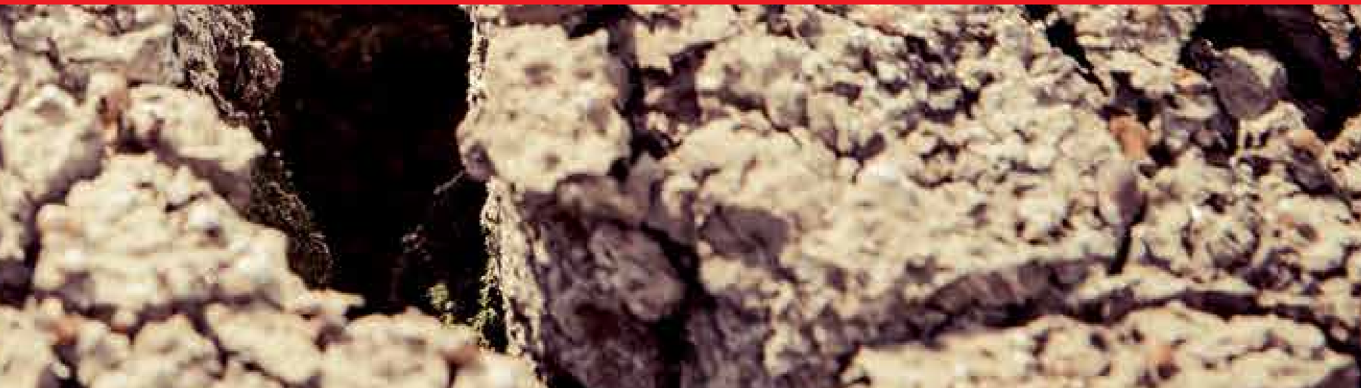
Arid Environments and Sustainability

Edited by Hasan Arman and Ibrahim Yuksel



ARID ENVIRONMENTS AND SUSTAINABILITY

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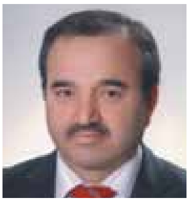
Meet the editors

Dr. Hasan Arman is a professor at the United Arab Emirates University, College of Science, Geology Department, since 2008. He received his bachelor's degree from Hacettepe University, Turkey, in 1984, and his PhD degree from the University of Arizona, USA, in 1992. He worked as a postdoc at the University of Nevada, Reno, USA, from 1992 to 1993. He was a faculty member at Sakarya University, Civil Engineering Department, Turkey, between 1993 and 2008. Dr. Arman has taught several different courses in undergraduate and graduate levels related to engineering, environment, and geology. His research interests include environmental degradation, sustainability, water resources, global warming, climate change, and renewable and sustainable energy sources. Dr. Arman has a number of publications in different peer-reviewed national and international scientific journals. In addition to be an editorial board member of several international journals, he also is acting as a scientific reviewer in many others. He was in organization committee of both 1st and 2nd International Conference on Renewable Energy: Generation and Applications (ICREGA) which was held in 2010 and 2012 in Al Ain, UAE.



Dr. Ibrahim Yuksel received his undergraduate degree from Gazi University, Ankara, Turkey, in 1988. His MSc degree was obtained from the MidKent College, Chatham, United Kingdom. In 2000, he completed his PhD degree at Karadeniz Technical University, Trabzon, Turkey. Since 2014, he has been teaching at Yildiz Technical University, Faculty of Civil Engineering, Department of Civil Engineering, Hydraulics Division, Istanbul, Turkey. Dr. Ibrahim Yuksel has over 30 years of experience in hydraulic engineering. His main interest is renewable and sustainable energy, especially hydro energy. He delivered a number of lectures in different European universities such as Italian, German, Portuguese, Hungarian, Polish, and Slovenian universities. Besides remarkable scientific experiences, he has administrative practices such as director, university board member, Erasmus coordinator, etc.

Contents

Preface

Arid environments are characterized by a severe lack of water besides high temperature. Such harsh conditions complicate plant growth, animal life development, and human social activities. Rainfall in arid environments may, in most cases, be associated with torrential events causing risk for extensive soil erosion. Large difference between daytime and night temperature furthers negative impacts on the environment in arid regions.

The term sustainability is derived from the Latin word *sustinere*. Sustain can mean "maintain," "support," or "endure." However, sustainability has different definitions in various disciplines; for example, sustainability in ecology is the property of biological systems to remain diverse and productive indefinitely. In more general term, sustainability is the long durability of systems and processes within various adapted environmental conditions. Sustainability is supported by three crucial pillars: environmental, social, and economic. The most important one among these three pillars is of course environmental sustainability. Without handling environmental sustainability issues, the other pillars weaken as they are highly dependent on the thriving system of the environment.

Studies on sustainability of arid environments are becoming more critical with the advent of urbanization and climate change due to serious threats to plant, animal, and social life. These studies certainly provide insights into the problems despite local and/or regional concerns. Nevertheless, sharing such experiences among the scientists and decision-makers will deliver comprehensive approaches to solve and emphasize solutions to specific or general sustainability problems. Due to the high vulnerability of arid environments, the associated problems require fast, effective, and stable solutions to avoid recurrence of similar problems in the future. For better, secure, and sustainable environment, decisive actions are absolutely needed.

This book is divided into four sections: "Land Degradation," "Arid Rangeland," "Climatic Hazards," and "Water Resources and Policies." Each section contains chapters addressing various issues related to arid environments and sustainability.

Several experts have provided progressive contributions for the development of this book. The editor and coeditor of the book are thankful for their remarkable collaborative support and efforts to complete this book. Finally, the editors would like to thank all the staff of IntechOpen for their invitation and enthusiasm during all the stages of development of the book.

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Section 1

Land Degradation

Chapter 1

Strategies to Enhance Sustainability of Land Resources in Arid Regions

Selen Deviren Saygin

Additional information is available at the end of the chapter

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Abstract

The ability to effectively maintain the functions of the ecosystem is closely related to the assessment of land resources within a conservation-utilization balance. Land degradation is one of the most significant environmental treats on arid region ecosystems in terms of the use of these resources. In this chapter, the aim was to attract the attention to land degradation processes in Turkey and analyze the current conditions in the context of policy-science interaction by performing the strengths, weaknesses, opportunities and threats (SWOT) analysis and develop the effective strategies for sustainable use of land resources. Thus, anthropogenic effects on sustainability of land resources and its relation with drought and productivity, and insufficient legal regulations were analyzed for developing strategies to enhance sustainability of land resources. Results showed that Turkey is at the point of breaking for sustainability of its natural resources. Insufficient topographic and soil conditions, administrative problems and negatively changing climatic conditions made the condition adverse. Therefore, the significant strategies were defined for sustainable resource management under the integrated approach from ecological, economic, political and sociological perspectives. In this context, assessments have been made in order to prevent weaknesses and possible threats to the sustainable use of this resource.

Keywords: land degradation, sustainability of land resources, SWOT, Turkey

1. Introduction

At the historical development of human beings, we see that many civilizations had been established from the hunter-gatherer system (the Neolithic period) to the premodern 9000 period that had caused the great pressures on natural resources [1]. It is known that human activities such as overgrazing, deforestation, wrong or inappropriate land uses/conversions and poor agricultural management practices are common causes of land degradation, but extreme climatic events also accelerate this process. It is reported that today 1.5 billion people worldwide are affected by land degradation processes [2]. Especially in arid and semiarid ecosystems, land degradation is one of the most significant environmental treats. The major problems encountered in terms of sustainable land management in these ecosystems are mentioned as the salinity, desertification and drought and soil erosion. However, these problems are defined in different forms in different sources. The result is the same for humans who base their life on agricultural bases. This is the gradual decline of the fertility capacity of the soil. At this point, it is extremely important that the soil, which is one of the main resources for living beings to survive on earth, is sustainable. Today, land resources in terms of soil and water are limited to meet the needs of future generations as we completely depend on these resources. In the world, it is estimated that 12 million hectares of land are degraded annually (corresponding to 23 ha per minute), which corresponds to 20 million tons of grain due to the results of drought and desertification. In the economical aspect, annual cost of land degradation is estimated to be about US$300 billion. This includes losses to both agricultural production and other ecosystem services [3].

To combat land degradation processes, many strategies have been defined by both governments and intergovernmental platforms under several titles such as United Nations Sustainable Development Goals (SDGs), Food and Agriculture Organization of the United Nations (FAO), Global Soil Partnership and Land Degradation Neutral World. In particular, Goal 2 (end hunger), Goal 3 (good health and well-being), Goal 12 (responsible consumption and production) and Goal 15 (life on land) of the Sustainable Development Goals (SDGs) that are planned to be reached for the period covering 2015–2030 include measures and policies related to the use of land and water resources [2]. Of course, the applied agricultural policies have direct and very important effects on land use. The subsidies, incentives and taxes imposed by governments have great implications for which crops are grown and where land is well managed. Inappropriate land management practices applied in marginal areas and fragile ecosystems that are sensitive to climatic, topographic and soil conditions cause the rapid deterioration of land resources. But, land resources are limited and demands for different land-use types especially in the developing countries are greater than the available land resources and these demands become more pressing on natural resources [4]. And so, the only way to protect and sustain soil and water resources from negative effects of erosion, salinity and desertification and other land degradation types in fragile ecosystems is to prepare and enforce appropriate land-use plans. Because of that, sustainable resource management can only be successful if it is based on appropriate land uses. In summary, sustainable promotion of soil and land management is necessary for the provision of healthy food and the environment. Within the scope of this chapter, the aim is to attract attention to land degradation processes in arid and semiarid regions (mostly focused on Turkey's conditions), to analyze the conditions in terms of policy-science interaction by performing situation analysis (SWOT) and develop the effective strategies for sustainable use of land resources under arid and semiarid Turkey conditions.

2. Definition to the causes and results of land degradation in arid and semiarid regions: current situation in Turkey

As mentioned above, land degradation is one of the major environmental problems worldwide and has become particularly severe in the last decades in Turkey [5]. It causes the significant reduction of the ecosystem functionality with unfavorable effects on biodiversity, desertification and water resource quality [6–9]. FAO [10] figured that the main causes of land degradation are the deforestation, population growth, urban expansion, pollution and waste disposal, climate change and unsustainable land management practices, and their results led to discovering significant problems especially in the arid ecosystems having great water scarcity to survive ecosystem services at the optimal conditions. These problems are defined as biodiversity loss, salinization and sodification, nutrient imbalance, compaction, sealing, pollution, acidification, erosion and loss of soil organic carbon. As a result, water scarcity, food and nutrition insecurity, rapid climate change, poverty and social insecurity, migration and reduction of the ecosystem services are basically affecting our lives.

The rate of land degradation processes is closely related to the interactions between climate, soil, land use and topography. Today, Turkey is classified as degraded in terms of soil according to the degradation map [11]. In this context, it was stated that a large part of Turkey is rated highly susceptible to desertification in terms of climate, soils, topography and land cover status [12], although no region could be classified as "desert" in the country based on the general evaluation of the 1965–2007 period using the Aridity Index [13]. Ninety percent of Turkey's total land area is climatologically classified as arid and semiarid regions; especially, Aksaray, Cihanbeyli, Ereğli (Konya), Iğdır, Karaman, Karapınar, Konya, Nallıhan and Niğde stand out in the semiarid-very arid border. In general, Thrace, Central Anatolia, the interior of the Central Black Sea and eastern Anatolia are regions where arid and semiarid areas spread [13].

Other significant studies related to the long-term variability of climatic conditions over the rainfall regions of Turkey mostly indicated that annual and seasonal precipitation totals have been in the decreasing trends for many stations in Turkey, particularly at those in the Aegean and Mediterranean regions and South-eastern Anatolia and the continental interiors of Turkey that have significant potential to be arid lands in future. And it is estimated that these regions will become more sensitive to desertification in the future with anthropogenic effects such as forest fires, land conversion, urbanization, pollution, etc. [13–20]. Considering the variation of rainfall erosivity values, a trend analysis for the Mediterranean part of Turkey was performed (**Figure 1**) [21]. And, the obtained results showed that rainfall erosivity values statistically increased in the period of 1993–2004. Not surprisingly, increasing rainfall intensities led to increase in flooding and water erosion risk in several parts of Turkey [22, 23]. This situation is not only specific to the Mediterranean region but also to the whole of arid areas. Although there is a decrease in the amount of rainfall with global warming, climate change scenarios state that rainfall intensities in dry areas significantly tend to increase [24]. Another potential threat is the degradation of soil moisture balance and the depletion of groundwater levels throughout the country as a result of reduced winter precipitations [17].

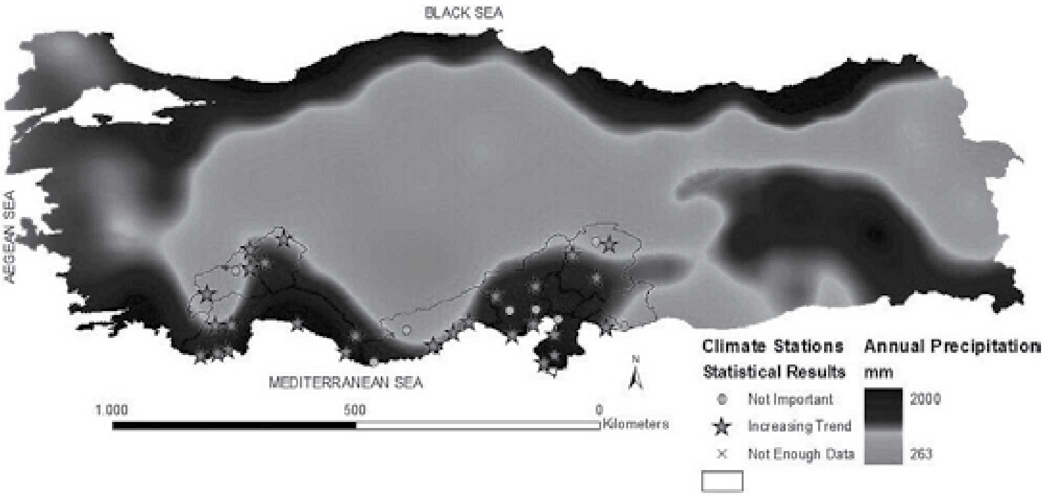

Figure 1. Trend analysis result for rainfall erosivity values in the Mediterranean part of Turkey.

At the basis of all these problems are actually anthropogenic effects. People in fragile ecosystems promote land degradation processes due to land-use conversions by farming in fragile soils and applying poor crop management techniques. And, those facilities have significant effects on salinization and nutrient exploitation in terms of degraded natural soil and water interactions. [25]. Another drastic effect on resource management of land-use transformations in these ecosystems could be mentioned as the mineralization of soil organic carbon (SOC) by cultivation activities. These changes under the Mediterranean climate conditions have been closely examined by various researchers [26–28]. And, the effects of these conversions on land resources, global warming and soil are being discussed frequently in recent times [29]. As reported, three main reasons of the global increase of CO_2 and other greenhouse gas emissions, resulting in global warming, are fossil fuel combustion, cement manufacturing and land-use changes [30]. It is known that the conversion from natural to agricultural ecosystems, tillage and soil degradation with erosion and other processes in the world resulted in a reduction of about 60% of carbon stock in the soil from the beginning of agriculture 10,000 years ago [31–33]. It is an important fact that the effect of agriculture on greenhouse gas emissions is increasing day by day in terms of CO_2 equivalent (**Figure 2**) [34]. In addition to inappropriate mechanization techniques, exploitation of grassland and forest areas in fragile ecosystems, especially for agricultural activities, is triggering this situation.

Soil organic carbon (SOC) is the significant parameter to evaluate land-use conversions' effects on vulnerability of soil erodibility. This unsuitable land-use changes cause the decomposition of aggregates as a result of organic matter being oxidized [5, 35, 36]. In this context, a comprehensive investigation on the effects of changes in land-use type on some soil properties was performed in a Mediterranean plateau and searched for land-use effects for three adjacent land-use types including the cultivated lands, which have been converted from pastures for 12 years, fragmented forests and unaltered pasture lands [29]. Results indicated that cultivation of the pastures caused the degradation of soil physical properties and increased the soil susceptibility to the erosion under the limited soil depth conditions in the southern Mediterranean

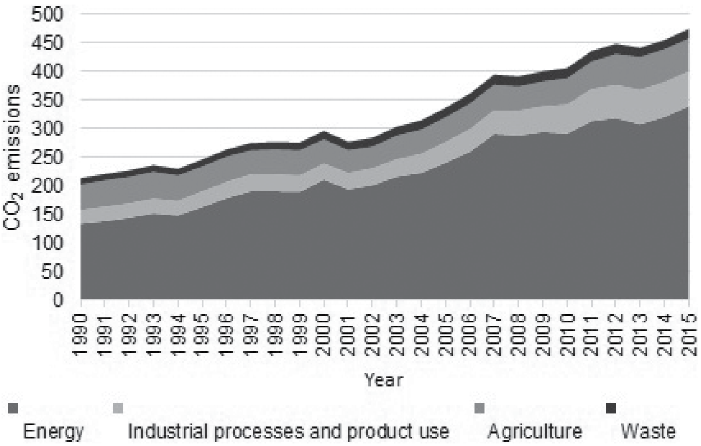

Figure 2. Greenhouse gas emissions according to the sectors in Turkey [34].

highlands [29]. Similarly, land-use transformation effects on soil erodibility in the Central Anatolian conditions were investigated [37]. And, findings showed that soil organic matter content, hydraulic conductivity and soil erodibility value statistically changed with changing land use, and soils of the recreational land and cropland were more sensitive to water erosion than those of the woodland, grassland and plantation usage. More recently, the changes in aggregate-associated and labile soil organic C and N fractions were evaluated after conversion of a natural forest to grassland and cropland in northern Turkey [38]. And, the results showed that long-term conversion of forest to grassland and cropland significantly decreased microbial biomass C, mineralizable C and physically protected soil organic C. Recently, it was reported that 70% of SOM was lost from agricultural soils due to cultivation practices; however, there is no definite information about dehumidification ratios [39]. Moreover, when evaluated in terms of the levels of organic matter in Turkey, it is less than 1% in two-thirds of soils [40–42].

Not surprisingly, the lower organic matter contents make the soil more susceptible to erosive forces in these fragile arid and semiarid ecosystems. In addition to that, considering the topographical conditions, the country generally has a mountainous topography with higher slope degrees and shallower soil profile depth. With 47.98% of the total land having 'steepness of slope' greater than 20% and 62.15% of land, the slope greater than 12% was not suitable for machinery agricultural activities. It also accelerated the soil erosion risk [43]. Today, 16.4 million hectares of the 27.7 million hectares of agricultural land soil erosion is the major problem in Turkey. If an overall assessment of the erosion potentials of Turkey's soil is to be made, it can be said that more than 75% of the land is at risk of erosion at different levels [44, 45]. It was reported that suspended sediment yield was 155 ton y^{-1} km^{-2} or 119 m^3 y^{-1} km^{-2} based on the detailed river observation in Turkey [43, 46], considering that the soil formation rate is naturally 1 mm within 200–400 years [47]. In this way, the soil formation rate was calculated as "0.025 mm y^{-1}, 0.025 m^3 ha^{-1} y^{-1} or 0.0325 ton ha^{-1} y^{-1} if taking into consideration the upper limit of soil formation rate for arid and semiarid conditions of Turkey. Accordingly, the rate of soil loss was estimated approximately 48 times higher than the rate of soil formation in Turkey [43]. It is also well known that for agricultural purposes the breaking of the natural soil formation rates 40 times and for other reasons, such as breaking with up to 100 times more soil losses occurred in worldwide [47, 48].

Other significant problems encountered in arid and semiarid regions in Turkey are drought, salinity and desertification due to lack of precipitation, high evapotranspiration rates and unsuitable land management practices [49]. Today, agricultural sector is one of the most important users of water resources in Turkey. Annually, we are economically using 44 billion cubic meters of 112 billion cubic meters of water resources, and 74% of this water is only being used for agricultural activities [50]. Excessive and unsuitable use of both surface and subsurface waters for agricultural purposes led to significant changes in the quantity and quality of water resources. In the world, 60 million hectares, which account for about 20% of the world's irrigated areas, are facing serious salinity problem. And, more than 50% of these areas are located in India, China, USA and Pakistan. Turkey is also affected by irrigation-derived salinity at considerable levels. Today, 1.5 million hectares of soils have salinity problem due to improper management of irrigation and inadequate drainage in Turkey [2]. As a result of unsustainable agricultural practices, a considerable amount of agricultural land is put out of production each year. This situation results in reducing agricultural productivity and limiting agricultural production areas [49]. Thus, it is estimated that increased salinization of arable land will led to a land loss of 50% in 2050 [51]. At the beginning of the causes that increase the activity of salinity in these regions is the drought. In Turkey, on average, a moderate drought every 6 years and a most severe drought every 18 years are observed. For this reason, World Meteorological Organization (WMO) listed Turkey among the 76 countries that have the risk of drought [50, 52].

According to the drought predictions, the tendency of meteorological drought in our country to turn into agricultural drought is rather high [53]. This is in our country that uses 74% of total water for agricultural purposes; the fact that agricultural drought is one of the most important limiting factors for the agriculture sector in terms of having enough moisture in the soil during the plant development periods for agricultural production [50]. According to the 2020, 2050 and 2080 projections in Turkey, a decrease in production rates of the grains such as wheat, barley, rye and oat by 4.9, 8.3 and 13.8 per percent, respectively, due to climate change and drought is estimated [54]. Considering that 80% of the 24 million hectares of agricultural land is rainfed, it is clear that if necessary measures are not taken, agricultural production will be adversely affected in the future from the climate change processes. As a result, the sustainability of land resources in semiarid and arid ecosystems, such as Turkey that has high sensitivity to land degradation in terms of climate, soil and topographic conditions, is directly related to the effective implementation of sustainable land management practices. And, it can be achieved on the condition that the science-policy interface is actively formed.

3. Measures and strategies at a national scale and its potential and actual effects on sustainability

Successful land resource management requires action to be taken at the level of individuals, governments and even intergovernmental organizations. In this context, sustainability of the collaboration and interactions in the science-policy interface, improvement of the existing sources of information in terms of databases of land resources and the adaptation of the legal regulations under the sustainable land management approach are significant issues to reach the desired targets.

Related to the subject, revised soil charter [55] defined the responsibilities under the three main groups, which are individuals and private organizations, government and intergovernmental organizations, to overcome degradation process and build restoration of degraded areas. The success of national scale works related to land resource sustainability is closely linked to the actions and strategies that governments will implement. For that, 10 significant actions to be realized by governments are defined [55]. Among them, the last three actions (VIII, IX and X) emphasize the need to develop the land and soil information systems to combat climate change and land degradation processes in terms of sustainability of land resources effectively.

To more effectively and sustainably combat desertification and erosion throughout Turkey, both national and international projects have to been seriously implemented. National Soil Erosion Map by USLE/RUSLE algorithm (Universal Soil Loss Equation – Revised Universal Soil Loss Equation) [56] is one of the most important attempts by General Directorate of Combating Desertification and Erosion bureau. In this context, constantly updated 'Erosion Monitoring System' is preparing for monitoring studies and creating data archive in the web [57]. It is aimed to gather available information throughout the country related to applied or planned soil conservation practices. It is supported with web-available system for applying different scenarios to estimate its effects on soil loss ratios [12]. Another important monitoring system is created for the problem of desertification. For that, a risk map has been established by determining the vulnerability classes of desertification-sensitive arid and semiarid lands of Turkey [57]. Studies at national scale are also being conducted in the same way to evaluate the risk of wind erosion and take effective precautions against to it.

In addition to this, considerable steps have been taken with the efforts to increase the presence of forests and the improvement of the existence of damaged forests. Over the last 37 years, total forest area has increased by 1.3 million hectares with afforestation projects. For future projections, it is aimed to increase the total forest area from 27 to 30% by 2023 by Ministry of Forestry and Water Affairs. Afforestation of degraded soils by converting into forests or other perennial land uses has a large potential of soil organic carbon sequestration. It will enhance the carbon accumulation in soil organic matter [32].

Other significant projects on management of limited land resources in Turkey are related to watershed managements, soil and water resource monitoring facilities, drought, desertification, snowslide, flood and landslide control and monitoring systems, rehabilitation of degraded areas in the context of Land Degradation Neutrality approach have been progressed by Ministry of Forestry and Water Affairs.

The Ministry of Food, Agriculture and Livestock, which is also responsible for combating climate change in Turkey, has various projects, strategies and policies related to agriculture as follows [58–61]:

- *Land Consolidation Strategy* aims to increase the efficiency and reduce the energy usage by reaching the optimum size of the enterprises. In Turkey, 5.1 million hectares of land consolidation work have been completed, and it is continuing at 1.9 million hectares area by the end of 2015. Land consolidation studies for 14 million hectares of land are planned to be completed by 2023.

- *Organic Farming Activities* aim to increase soil fertility in natural terms in the long term considering ecological conditions, to prevent soil and genetic resource erosion, to protect water quantity and quality, to use renewable energy resources and to help save energy.
- *Good Agricultural Practices* aim to ensure that agricultural production is done for sustaining the environment, human and animal health, protection of natural resources, supplying the traceability and sustainability in the ecosystem.
- Environmentally Protected Agricultural Land Conservation Program (ÇATAK) aims to give support payments for farmers who prefer ecofriendly agricultural techniques and cultural practices. Grant support is provided for the conversion of in-field irrigation systems to closed and pressurized systems within the framework of the Program for Supporting Modern Irrigation Methods to Support Water Saving and the Support Program for Rural Development Investments.
- *Drought Management* supports Agricultural Drought Provincial Crisis Centers in 81 cities that were established and the provincial agricultural drought strategies and action plans for the years 2013–2017 were prepared and put into effect in order to reduce the expected drought more frequently due to climate change.
- *Agricultural Insurance Applications* are being done for floods, hurricanes, etc., which are increasing in number due to climate changes. They aim to compensate for the risks arising from meteorological disasters. Through the Risk Management strategy in agriculture, it is aimed to ensure the sustainability of production by ensuring the products of the producers exposed to such risks.

And several agricultural Research & Development studies pursue to reduce the energy use in agriculture, sustainable resource use, development and improvement of drought-tolerant plants, improvement of methods and tools in irrigated areas in dry periods and development of land processing methods and tools providing carbon capture in the soil. The others related to some information technologies carried out in our country within the scope of action plans to be taken by governments are "land use land use conversion and forest (LULUCF)," "determination of the problematic agricultural areas," "agricultural monitoring and information system project (TARBİL)," "farming registration system" and "rural database project." All of these projects aim at the formation and development of reliable information systems related to soil and land-use strategies.

Recently, the significant project that stands out in crop/soil management is the "National Agriculture Project" that has been started by the Ministry of Food, Agriculture and Livestock in 2017. Its original aim is to promote sustainable agriculture by considering the existing ecological and economic conditions and the needs of Turkey. In this context, 21 products that are important in terms of human nutrition, health and animal production, which are strategically and locally important in our country (wheat, barley, rye, rice, Dane corn, triticale, oats, lentils, chickpeas, dry beans, cotton, soybean, oil sunflower, canola, Aspir, tea, hazelnut, olive oil, potatoes, onion and forage plants), will be supported on 941 agricultural areas and planned production will be passed. To define the supported product on a specific area, a decision support system has been established that includes more than 1 billion data taking into consideration long-term output statistics, the crop rotation, climate, soil and topography conditions, water restriction data (current water potential and vegetation water consumption), present legal regulations on soil conservation and public and academic proposals. Within the scope of this project, "fertilizer usage guidelines" was prepared for total 941 agricultural basins to prevent from being contaminated with excessive fertilization and increased productivity. And, 211 large plains have been identified and their boundaries have been determined in order to ensure effective protection of agricultural land. It is planned that these 211 large agricultural basins will be declared as a protected area by the decision of the Council of Ministers and protected effectively. New arrangements have been made in order to bring unused agricultural lands for various reasons (property issue, immigration, abandonment of farming, etc.) to agricultural production and the economy of the country. Irrigation and land consolidation projects will be applied in the scope of this project. Thus, it is aimed at increasing the production capacities of the soil by adaptation of modern production/irrigation techniques within the soil and water resource conversation approach.

However, discussions about the legal, technical, socioeconomic and environmental dimensions of sustainable land and soil management in Turkey clearly showed that land-use planning for industrialization, urbanization, transportation and tourism, etc., with the contribution of the gaps in the legal regulations creates a serious pressure on our land resources, the soil functions are deteriorated and it causes the subsurface and above-ground ecosystem services to disappear. In particular, the concept of "public good" in the law on soil conservation and land use has been brought to lead to the use of an instrument for the conversion of qualified agricultural lands to another uses.

In addition, databases already used in land-use plans have lost their validity. There is an increasing demand for detailed soil surveys in Turkey by scientists and technicians working on projects of sustainable soil and water management. Soil classes should be updated. It was produced within the 1938 Soil taxonomy named as the old American classification system [62], and semidetailed maps made 30 years ago need to be updated nationwide at 1/25: 000 scale to meet today's needs. The information-based land-use planning period, which includes soil series and important phases, should be urgently passed. A more systematic case assessment on land resource sustainability in Turkey is shared below with the help of SWOT analysis.

4. Situation analysis, SWOT: soil and water resources and sustainability in Turkey

Strengths, Weaknesses, Opportunities And Threats (SWOT) analysis is defined as the strategic planning method used to summarize the key elements of your strategic environments [63]. In fact, it is thought as the first step in the strategic planning and it helps planners to identify the strategies of achieving goals by concentrating on the key subjects [64]. The SWOT analysis matrix was explained by [65] as shown in **Table 1**. Where the questions are to be asked in the analysis to reach the planned targets are expressed clearly.

	Strengths	**Weaknesses**
Opportunities	How do I use these strengths to take advantage of these opportunities?	How do I overcome the weaknesses that prevent me from taking advantage of these opportunities?
Threats	How do I use my strengths to reduce the impact of threats?	How do I address the weaknesses that will make these threats a reality?

Table 1. SWOT analysis matrix [65].

The method, commonly used for several business enterprises, has recently been widely used in sustainable planning of environmental resources in terms of changing demands and declining resources. For example, it was used to assess the rural tourism potential in Turkey [66]. Groundwater resource potentials were also evaluated in the Zakynthos Island in terms of sustainability with the help of SWOT analysis technique [67]. In addition, for more appropriate conservation and utilization of natural resource, this analysis technique could significantly be

Objective: strengths, weaknesses, opportunities and threats (SWOT) analysis for "land resources and sustainability in Turkey"

External factors		**Internal factors**	
Strengths (S)	**Weaknesses (W)**	**Opportunities (O)**	**Threats (T)**
S_1: Abundance of natural resources all over the country compared to the most severe arid regions in the World	W_1: Sensitivity for climate change and land degradation processes in terms of severe soil erosion, salinization, drought and desertification rates especially in semiarid and arid regions	O_1: A very young farmer population that can better understand and accept environmental issues	T_1: Predictions that the temperatures will increase and the irregularities in the precipitation regimes
S_2: The existence of legal regulations, e.g., laws and regulations related to the soil and water protection, land-use planning, natural resource protection and rural development	W_2: The shortcomings of the law and governmental regulations for sustainable land management strategies	O_2: Increased supports for farmers who especially implant the best management practices	T_2: The risk of deterioration in soil quality due to the applied national agricultural policies
S_3: The existence of action plans to combat erosion, climate change, desertification and protect biodiversity	W_3: Lack of reliable data on soil and water resources to protect the sustainable use of these resources	O_3: Opportunities to access the international funds for environmental protection	T_3: The risk of increasing anthropogenic pressures on land resources
S_4: Adopt and approve all international conventions of environmental and biological diversity by governmental and public organizations	W_4: Increasing pollution rates of soil and water resources due to agricultural, industrial activities and energy requirements	O_4: Increasing public interest for the nature-friendly production methods	T_4: The possible environmental risks to be encountered in the absence of science-policy coordination in legal regulations
S_5: The existence of strong academicals, technical and administrative infrastructure	W_5: Unprevented land conversions due to political pressures and gaps in the legal regulations	O_5: The development of nature-friendly new production technologies	T_5: Placement of the perception that the unsuitable land conversions can be made to provide energy production and raw material
	W_6: Lack of coordination and integration efforts between public, academic, private, governmental and nongovernmental organizations for sustainable planning of natural and human resources	O_6: The development of existing policies based on the protection-use balance with the aid of contribution of new information technologies due to the necessity of harmonization process in the EU and international obligations	T_6: Increase in immigration rates and social-economic and cultural problems caused by the reduction of natural resources

Objective: strengths, weaknesses, opportunities and threats (SWOT) analysis for "land resources and sustainability in Turkey"			
External factors		**Internal factors**	
Strengths (S)	**Weaknesses (W)**	**Opportunities (O)**	**Threats (T)**
Strategies (WT)			
WT$_1$: Reforming environmental, agricultural and industrial policies to establish sustainable resource use			
WT$_2$: Updating databases used in monitoring climate change and land degradation processes			
WT$_3$: Preparing updated land-use plans in accordance with the needs of the ecosystem, taking into account the science-policy balance			
WT$_4$: Planning and implementing research, experiments and extension studies related to the defining suitable land-use types for the ecological conditions of the selected region			
WT$_5$: The application of dissuasive punishment to land users exceeding pollutant limit values by periodically measuring the runoffs in terms of transported sediment-associated pollutants and water quality in the microwatershed scale			
WT$_6$: Supplying an acceptable level of farm income by reducing income variability for reducing the pressure on especially marginal lands			

Table 2. SWOT analysis for soil and water resources and sustainability in Turkey.

used [68] for village planning. Similarly, significant strategies were proposed for sustainable farming system management based on farmers' needs by conducting SWOT analysis in rural areas of Shadervan district, Shouahtar Township, Iran [64]. Under the fragile arid and semiarid climate conditions, it is vital to make strategic planning to manage land resources in sustainable manner. As a first step for long-term effective planning in Turkey conditions, SWOT analysis was performed to draw the situation including the strengths, weaknesses, opportunities and threats as the internal and external effects on developing strategies on sustainability as given in **Table 2**.

5. Strategies to maintain the conservation-utilization balance for sustainability in arid regions

In light of the performed SWOT analysis for "Land resources and Sustainability in Turkey," six threats and six weaknesses were identified, and to overcome their effects, six significant strategies were recommended as outlined below.

5.1. Strategy WT$_1$

Unfortunately, it has been assessed that the soil and water resources in our country cannot be protected by effective and comprehensive legislation. And so, reforms are needed in the existing legislation, taking into account the conservation-use balance in relation to the protection of natural resources $[W_{2\text{-}5} - T_{2\text{-}4\text{-}6}]$.

5.2. Strategy WT$_2$

National scale studies such as monitoring and assessments of soil degradation types, e.g., desertification, erosion and effects of climate change and global warming on sustainable land management have been largely based on unreliable datasets, and so, they need to be updated for effective planning and monitoring of land resources. In order to do that, comprehensive soil survey and mapping studies should be carried out. In addition, species especially in arid regions should be identified for preventing biodiversity losses, and necessary measures should be taken for sustainability [$W_{1\text{-}3}$ – $T_{1\text{-}6}$].

5.3. Strategy WT_3

It should be followed after the activities specified in Strategy 2. It is very important to keep up the conservation-use balance in the land-use plan, which is prepared with updated data. But, land-use planning in practice should be an integral part due to that land-use planning only for agricultural purposes is not sufficient for solving problems. District and regional planning and then land-use planning at the entire country level should be done. In the planning phase, it is necessary to include specialists working in the fields of law, economics and society, and landowners in order to effectively implement the plans besides natural resource specialists on the planning team [$W_{5\text{-}6}$ – $T_{2\text{-}3\text{-}5\text{-}6}$].

5.4. Strategy WT_4

It suggests that research and experiments should be carried out to find most suitable land-use types in the region that are planned to be proposed primarily in land-use plans and that the results obtained in the determination of region specific uses should be objectively introduced to the people of the region and should be tested for validity of suitability by taking into account long-term forecasts and forecasts of climate change and the sensitivity of land resources to these changes. Unintended use of agricultural areas should be prevented. For that, breakup of agricultural lands, especially nonagricultural use of irrigated agricultural land, and agriculture in unfavorable agricultural land will be prevented and land consolidation services will be accelerated [W_1 – $T_{1\text{-}6}$].

5.5. Strategy WT_5

Various pollutants sourced by industrial facilities or excessive consumption of fertilizers or chemicals have the ability of easily transporting in the soil-water air cycle and affecting the ecosystem services negatively. In this context, it is proposed to establish mobile-test centers throughout the country to monitor pollution in soil and water resources and to apply effective punishments to those within the basin scale where limit values are exceeded as a result of periodically planned measurements. And, spread of the good agricultural practice techniques, establishment of modern irrigation and drainage systems in order to prevent soil salinization, planning and implementation of budgeting for drought and salinity-resistant species determination studies and identification of potential rehabilitation sites should be performed especially in the degraded arid and semiarid areas of Turkey. Proper fertilization and soil conservation strategies must be introduced. The content of soil organic matter in arid and semiarid regions should be increased with the use of animal fertilizers together with the application of stubble and green fertilizer usage techniques. Cultural and technical measures (such as fertilization, seeding and soil and water conservation measures) must be taken with pasture management to protect natural grassland areas where rainfall is insufficient or unevenly distributed. In areas having higher potential for rehabilitation, measures to prevent land degradation should be planned and enforced. Biological fighting methods should be preferred in combating harm [$W_{4\text{-}5\text{-}6}$ – $T_{2\text{-}3}$].

5.6. Strategy WT_6

The topographic and climatic conditions of Turkey limit the width of the suitable land in rural areas. Besides, the land is very fragmented in the way of inheritance, which leads farmers to use marginal lands for agricultural facilities, and it causes the land degradation process in terms of deforestation, land conversions, etc. These activities shortly give irreversible damage to areas where high slopes, shallow soil profiles and inadequate vegetation coverage are the key properties for degradation. For this reason, it is extremely important to supply an acceptable level of farm income to the farmers. In this context, rural development must be realized in agriculture. For that, agricultural income should be increased steadily, the standard of living should be increased and resources should be used more effectively and economically. Thus, the way to be followed is the regional planning of production patterns with high profit margins based on the conservation-use balance of natural resources in order to reduce the pressure on land resources considerably [W_6 – $T_{3\text{-}6}$].

6. Conclusion

In Turkey, the effects of land degradation are considered to be mostly experienced in the inner and central Anatolia regions where the arid and semiarid areas dominate. Intensive deforestation, industrialization and rapid population growth in coastal regions have been defined as the significant threats for accelerating the impacts of climate change throughout the country and limiting the sustainability of natural resources with the aid of topographical and climatic insufficiencies. In this context, first, current situation of land degradation processes and its causes and results in Turkey were discussed and then the measures and strategies enforced in the national scale were summarized. Under the light of current situation, SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was performed to recommend the strategies for overcoming the weakness and possible treats on sustainable land resource management. These strategies were mainly explained under the headings of deficiencies in legal regulations in Turkey: the necessity of making comprehensive land-use plans not only at the agricultural purposes but also at the regional and national scale, renewal of insufficient and unreliable databases of natural resources in terms of monitoring land degradation and climate change processes, supplying of the coordination and integration among governmental, academic, private, nongovernmental organizations and land users and dissemination of environmentally sound management practices. Finally, it is concluded that sustainable resource management must be ecologically, economically, politically and socially integrated in fragile ecosystems such as Turkey.

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Section 2

Arid Rangeland

Chapter 2

Simulating the Productivity of Desert Woody Shrubs in Southwestern Texas

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Additional information is available at the end of the chapter

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Abstract

In the southwestern U.S., many rangelands have converted from native grasslands to woody shrublands dominated by creosotebush (*Larrea tridentate*) and honey mesquite (*Prosopis glandulosa*), threatening ecosystem health. Both creosotebush and mesquite have well-developed long root systems that allow them to outcompete neighboring plants. Thus, control of these two invasive shrubs is essential for revegetation in arid rangelands. Simulation models are valuable tools for describing invasive shrub growth and interaction between shrubs and other perennial grasses and for evaluating quantitative changes in ecosystem properties linked to shrub invasion and shrub control. In this study, a hybrid and multiscale modeling approach with two process-based models, ALMANAC and APEX was developed. Through ALMANAC application, plant parameters and growth cycles of creosotebush and mesquite were characterized based on field data. The developed shrub growth curves and parameters were subsequently used in APEX to explore productivity and range condition at a larger field scale. APEX was used to quantitatively evaluate the effect of shrub reductions on vegetation and water and soil qualities in various topological conditions. The results of this study showed that this multi modeling approach is capable of accurately predicting the impacts of shrubs on soil water resources.

Keywords: arid rangeland, creosotebush, mesquite, ALMANAC, APEX

1. Introduction

Rangelands cover 31% of the total land base of the U.S. and occur mostly in western regions [1]. Western rangelands are mostly in arid and semi-arid regions that are subject to low and variable precipitation, high evaporative demand, nutrient poor soils, high spatial and temporal variability in plant production, and low net primary production [2]. Arid and semi-arid rangelands are susceptible to desertification as the result of cumulative threats such as extreme weather events (e.g. drought), land use change (e.g. suburbanization), inappropriate land management (e.g. livestock overgrazing), and invasion by shrubs and other woody plants [3, 4]. Among these threats, plant invasions are considered as one of the most serious problems in much of the southwestern U.S. [5]. Encroachment of woody shrubs into grasslands has been commonly observed in the arid and semi-arid regions and often reported [6–9]. Encroachment can be defined as increasing density, cover and biomass of shrub and/or woody species in open canopy systems [8]. These woody shrubs are indigenous species that have increased in density or cover because of changes in climate variables (i.e. warmer and more humid conditions), land use modifications, or decreased frequency of disturbance regimes [8, 10, 11]. Extensive expansion of shrubs and woody plant into grasslands has caused largely irreversible changes in ecosystem function (e.g. alterations in landscape net primary production pattern and reduction plant biodiversity) accompanied by increased water erosion, runoff, and leaching. This has also resulted in decreased forage availability for domestic livestock and wildlife [8, 12–18].

In the southwestern U.S., at lower and more level surfaces, many grasslands have been encroached on by two invasive woody shrubs, creosotebush (*Larrea tridentate*) and honey mesquite (*Prosopis glandulosa*) [7, 16, 19]. Densities of creosotebush and mesquite have increased in desert and arid rangelands in the southwestern U.S. since late in the nineteenth century [20, 21]. The dramatic increases in the density and cover of creosotebush and honey mesquite have greatly affected extensive areas of former desert grassland that were originally dominated by perennial C_4 grasses including black grama (*Bouteloua eriopoda*) and blue grama (*Bouteloua gracilis*) [20, 22, 23]. Creosotebush is a xerophytic, evergreen, perennial shrub that has a well-developed lateral root system extending far beyond the area under the leaf canopy. This root system allows it to outcompete neighboring plants [12]. Due to a deep, non-overlapping root system and high water use efficiency, creosotebush can maintain lower levels of productivity during dry and hot periods, with growth only stopping during extreme drought [24–26]. Like creosotebush, honey mesquite is highly tolerant to drought because it can draw water from the water table through its long taproot (up to 58 m in depth) [27–29]. Also, mesquite can persist on sites where little or no ground water is available by growing lengthy shallow lateral roots [30]. Fisher et al. [31] reported that mesquite can survive under water limited condition with reduced leaf area, increased thickness of the leaf cuticle and almost complete cessation of growth. Creosotebush and mesquite have different invasive strategies in desert and arid rangelands. Mesquite produces seeds between June and September, which are dispersed by the animals [32]. Mesquite seeds germinate quickly; sprouting in less than 5 days [33]. After germination, it usually takes 10 days until the first true leaf, or cotyledon, is completely developed [34]. In early seedling development, mesquite quickly grows its deep taproot under limited water conditions. Its taproot grows shorter with sufficient water than in dry soil conditions [33, 35]. Based on these results, mesquite invasive strategies are related to quick germination and fast growth of deep roots under limited water conditions. While mesquite has high germination rate, creosotebush has low germinability and requires more water to sprout seeds [36]. Once creosotebush seeds successfully establish in the soil, however, creosotebush can live over a 1000 years by reproducing clones [37].

As creosotebush and mesquite have expanded over large areas of former desert grasslands, control of these invasive shrubs is playing an increasingly important role for restoring lost ecosystem services by increasing perennial grasses. Increase in the density of perennial grasses improve soil quality, increase plant richness, and provides forage for livestock and wildlife [13, 14, 17, 18, 38]. Range managers have employed a variety of management practices to remove existing shrubs such as fire [39], herbicide [40], and physical removal [41] (**Figure 1**). However, these practices have common limitations: logistical difficulties and side effects potentially harmful to habitat restoration [42]. These control efforts often target only one part of the life cycle of the invasive species [42]. Moreover, attempts at control have been largely decreasing due to increasing costs [43]. An effective control strategy for invasive shrubs should therefore address these challenges posed by high cost, logistical difficulties, high risk impacts on non-targeted species, and both invasion and vegetation dynamics related to climate change. Also, a successful control strategy should be designed to control the targeted invasive species and to predict their effectiveness under specific environmental conditions. Process-based models can be used to assist range managers in identifying best management strategies through providing various outcomes of short- and long-term western rangeland conditions responding to different land management strategies and rapid changes in climate and other physical processes [44, 45]. To develop process-based model systems for assessing the impacts of creosotebush and mesquite in rangelands, it is important to understand factors that determine their distribution and abundance and how these relate to environmental factors. It is crucial to optimize their plant parameters describing growth in models.

Productivity of creosotebush clones is highly dependent on water availability [35, 47–50]. If there is sufficient water, creosotebush increases growth rate as new tillers initiate within a clone [35, 51, 52]. Mesquite productivity is also affected by water availability. According to Easter and Sosebee [52] and Ansley et al. [35], when irrigated, mesquite shrubs produce more foliage, have higher canopy cover, have higher transpirational water loss, and have lower root-to-shoot mass ratio than non-irrigated mesquites in western Texas. Soil type is also an important factor for creosotebush and mesquite establishment as determined by the soil nutrient availability as well as the soil physical characteristics. Soil physical characteristics are important because they influence surface infiltration and surface percolation [53]. Deeper horizons enriched by clay or calcium carbonate have deeper percolation depth and water availability, whereas fine-textured vesicular subsurface and surficial soil horizon development can limit infiltration. These soil characteristics differentially change availability of water for desert plants [53–57]. Landscape position also affects vegetative growth because it determines the

Figure 1. Photographs of rangeland management practices: (a) burning, (b) aerial herbicide spraying, and (c) excavator grubbing. Source: Adapted from PSSAT [46].

time interval between receipt of rain and its infiltration into the soil [58]. For example, creosotebush and mesquite do poorer on steep slopes with coarse, shallow soil [59–61] which have more runoff and less water available to plants [62]. Hamerlynck and McAuliffe [26] reported that branch mortality of creosotebush tended to increase on hillslopes, while no dead plants were found in alluvial sites.

Based on these results, creosotebush and mesquite growth varies with different rainfall, different soil, and different landscape position. Simulating creosotebush and mesquite growth chronological patterns in different desert rangelands and simulating the effects of control of these two invasive shrubs on vegetation and soil and water qualities are important when trying to control shrub productivity under various climate and soil conditions in the long term. Scaling up from small-scale experiments to large scale field-based monitoring is an important step for reducing the long-term productivity of creosotebush and mesquite under various climate and soil conditions in future. Process-based models can simulate the effects of precipitation and geomorphic patterns in detail, estimating apparent contradictory effects. They can project variation in creosotebush and mesquite production across several different landscapes and climatic conditions. Such models can be used systemically and in combination of characteristics of hydrology, soil erosion, land slope, and nutrient balance, which are hard to approach theoretically or technically in field and plot experiments. Two field-based process-level models, Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) and Agricultural Policy & Environmental eXtender (APEX), have potential to satisfy the needed characteristics in simulating creosotebush growth in desert rangelands.

The ALMANAC model is a process-oriented plant model that effectively simulates growth of a wide range of plant species [63, 64]. Strength of ALMANAC is its capability to accurately simulate competition for light, nutrients, and water for several plant species [65]. APEX can be applied for whole-farm or small watershed (up to 2500 km^2) analyses and can evaluate plant growth and yield of plant species, with focus on soil and water quality in small-scale watersheds [66]. Both models operate on a daily time step. APEX's major components are climate, hydrology, plant growth, nutrient cycling, soil erosion, carbon cycling, and agricultural management practices [67]. This model uses the ALMANAC plant growth algorithms to predict productivity for over 100 plant species [67]. APEX calculates several surface hydrological parameters (daily runoff, plant transpiration, soil evaporation, water stress for plant growth, and lateral subsurface flow) in different climates having variable land topological characteristics [67, 68]. Through APEX, the effects of control of invasive shrubs on soil quality can be calculated by the net differences in soil organic carbon (SOC) that occur with both invasive shrub control and no control sites.

Simulating plant development of evergreen desert shrubs like creosotebush requires some restructuring of the basic approach of degree days. Typically annual crops are simulated with a degree day sum from planting to physiological maturity for an annual growing season with crop specific values for the base temperature and optimum temperature [63–65, 69]. This approach has also been applied to warm season perennial grasses with annual growing cycles for the leaf area and biomass [70–73]. Unlike creosotebush, mesquite is a perennial deciduous tree that drops its leaves each year and then resumes growth the following spring, each year possibly attaining (in the absence of environmental stress) its potential leaf area index value for that year. When applied to trees in Canada, the degree day sum is for a series of years so that the trees can develop over several years [72, 74]. In those studies, the annual value for maximum leaf area index for the growing season increased each year to simulate how trees grow. The difficulties when attempting to transfer these approaches to desert evergreen shrubs are: (1) these shrubs do not lose their leaves during the winter of each season, (2) their phenological development is strongly tied to rainfall amount and patterns, and not just degree day accumulation, and (3) these shrubs can lose noticeable amounts of biomass due to tiller death during severe drought periods.

For this chapter, we used a multi-model combination approach, combining the strengths of two different models. A range of morphological characteristics of creosote and mesquite has been investigated from multiple locations. Based on field data, the ALMANAC model was used to create and optimize both the plant parameters and the growth curve. The resulting simulated biomass yields of creosotebush and mesquite were compared with the measured yields at the sampling locations. The resulting plant parameters and growth curve were subsequently incorporated into APEX to evaluate the effects of rainfall patterns and local soil and topological properties on the growth and productivity of the creosotebush within the sub-watershed scale in multiple regions of western Texas. The multi-model system can describe invasive plant growth and development interaction with environmental factors including light, temperature, soil characteristics and water availability. This is important to help understand why mesquite and creosotebush expand in rangelands. In addition, the multi-model system can quantitatively evaluate the invasive shrubs-perennial grasses competitive interactions in different environments and study the effects of control of invasive plants on soil organic matter and soil water content. This study will provide the desired outcomes in invasive plant management programs on rangelands.

2. Materials and methods

2.1. Morphological data collection

2.1.1. Study sites

2.1.1.1. Creosotebush

As described by Kim et al. [75], creosotebush morphological measurements were conducted at two sites in Pecos County (Fort Stockton 1 and 3), one site in Reeves County (Fort Stockton 2), and 10 sites in Brewster County (Alpine A, 1–9), all in Texas. Fort Stockton 1 was located in the right-of-way of Highway I-10, 91 km west of Fort Stockton. Fort Stockton 2 was also located in the right-of-way of Highway I-10, 61 km west of Fort Stockton. Fort Stockton 3 was inside Fort Stockton. Ten study sites (Alpine A, 1–9) were randomly selected within a 15 km wide distance on a large ranch 57 km south of Alpine. Alpine A was an airplane landing strip until 2005, so the creosote bushes there have been established for only 11 years.

2.1.1.2. Honey mesquite

As described by Kiniry [76], mesquite morphological measurement was conducted in the field located at the Grassland, Soil and Water Research Center near Temple in Bell County, Texas, U.S.

2.1.2. Soil and weather

For all study sites, elevation and soil type obtained from Web Soil Survey [77] (**Table 1**). Four weather stations which are closest to the study sites were selected for analysis. For Fort Stockton 2, the weather station in Balmorhea was selected, while for Fort Stockton 1 and 3, the weather station inside Fort Stockton was selected. The weather station inside Alpine was selected for Alpine 1–9. For mesquite study site, the weather station in Temple was selected. Total precipitation and maximum and minimum temperature from January, 1980 to March, 2016 were obtained from National Oceanic and Atmospheric Administration [78]. Detailed soil and weather information about these sites were described in the Kim et al. [75] and Kiniry [76] previous papers.

2.1.3. Morphological traits collection

2.1.3.1. Creosotebush

Measurements were performed from February to March in 2016. In Fort Stockton 1–3 and Alpine 1–3 locations, nine creosote bushes of different sizes were randomly selected for measurements of plant weight, height, crown diameter, and crown diameter perpendicular to the

Site ID	**Elevation (m)**	**Soil type**	**Percent soil particle (%)**		
			Clay	**Sand**	**Silt**
Creosotebush					
Fort Stockton 1	726	Sanderson association, gently undulating	28.0	35.2	36.8
Fort Stockton 2	908	Reakor association, nearly level	26.8	30.3	42.8
Fort Stockton 3	928	Reakor association, nearly level	26.8	30.3	42.8
Alpine 1	1172	Quadria, Beewon and Musgrave soils	41.9	32.7	25.4
Alpine 2	1172	Quadria, Beewon and Musgrave soils	41.9	32.7	25.4
Alpine A	1172	Quadria, Beewon and Musgrave soils	41.9	32.7	25.4
Alpine 3	1208	Chilicotal very gravelly sandy loam	18.9	46.9	34.1
Alpine 4	1208	Crossen-Cienega complex	18.1	43.3	38.6
Alpine 5	1207	Crossen-Cienega complex	18.1	43.3	38.6
Alpine 6	1215	Mariscal-Rock outcrop complex	18.5	43.0	38.5
Alpine 7	1220	Mariscal-Rock outcrop complex	18.5	43.0	38.5
Alpine 8	1211	Crossen-Cienega complex	18.1	43.3	38.6
Alpine 9	1191	Gemelo and Straddlebug soils	15.8	62.0	22.2
Mesquite					
Temple	183	Houston black clay	54	20	26

Table 1. Elevation, soil type, and physical properties of upper 50 cm of soil at all study sites located in reeves, Pecos, Brewster, and Bell counties in Texas, USA.

maximum crown diameter. Total fresh weights of each shrub and a subsample were weighed immediately following harvest. The subsample was dried in a forced-air 66°C oven until dry weight was stabilized. Shrub height was measured from the ground to the top of the highest leaf. The thickest tiller which had no damage from insects and disease was collected from each shrub sample in all study sites. A total of 174 tillers, including 9 tillers for Fort Stockton 1–3 and Alpine 1–3, 15 tillers for Alpine 4–9, and 5 tillers for Alpine A, were used for measurements of radius of cross section of sampled tiller, growth ring count, and growth rate. As the growth of creosote bush in a dry year can be negligible, we assumed that no rings formed during severe drought years. Detailed information about morphological measurements is described in Kim et al. [75].

2.1.3.2. *Honey mesquite*

Mesquite seeds were collected at the Grassland, Soil and Water Research Center and planted in pots in greenhouse. Mesquite seedling 0.08 m tall was planted in plots on March 1992. To avoid competition with herbaceous plants, intensive hand hoeing with spraying chemical weed control were done every year. The experiment was laid out in randomized completed block design with four replication. Each replication was seven rows (5 m) wide with a length of 37 m. Fertilizer was applied in early 1994 and 1995. Each spring in 1993, 1994, and 1995, 18 trees per replication were randomly selected for measurements of plant height, stem diameters at the base and at half total height, and number of main stems. Among those 18 mesquite shrubs, 3 shrubs were randomly selected to measure aboveground and belowground biomass during 1993–1995. Detailed information about morphological measurements is described in Kiniry [76].

2.1.4. *Intercepted light and leaf area measurements*

Photosynthetically Active Radiation (PAR) measurements were taken using an AccuPAR LP-80 Ceptometer (Decagon Devices, Pullman, WA, USA) to enable calculation of fraction of PAR intercepted (FIPAR). Measurement of FIPAR was taken between 10:00 and 14:00. Multiple readings were made under the shrub canopy within an 80 cm x 80 cm sampled area. Measurements of PAR were also taken with an external sensor above the shrubs concurrently with each below-canopy measurement. The multiple above and below readings were averaged to estimate FIPAR. FIPAR was calculated as ratio of PAR below canopy to PAR above canopy subtracted from 1.0. A subsample was harvested within each sample area for the light measurement. This subsample was brought to the laboratory for LAI estimation. In the laboratory, the subsample was weighed and then separated into green leaves, dark brown live woody material, and gray dead woody material. The leaf area was measured with a LI-3100 Area Meter (LI-COR Biosciences, Lincoln, NE, USA). LAI was calculated as leaf area of subsample (cm^2) divided by ground area sampled (cm^2), and then multiplied by the ratio of total fresh weight (g) to subsample fresh weight (g). The light extinction coefficient (k) was calculated by modified Beer's law. The value of k was calculated as the natural log of difference between 1 and FIPAR, and then divided by LAI. For creosotebush, PAR and leaf area measurement were taken from February to March in 2016, while the measurements were taken from mesquite shrubs in April, May, and July from 1993 to 1995.

2.2. Multi-model simulation of development

The field-based process-level models, ALMANAC and APEX, simulate processes of plant growth and soil water balance including light interception by leaves and dry matter production. Firstly, plant parameters were estimated based on 1) leaf area development; 2) development rate response to temperature; 3) radiation-use efficiency and physical descriptions; and 4) nitrogen and phosphorous concentrations in plant biomass (**Table 2**). In addition, ALMANAC accounts for the effects of stresses such as nutrient deficiency, drought, and temperature on plant biomass and LAI [65]. Plant parameter values and plant growth curve were optimized through ALMANAC application using the field data. ALMANAC has been used to simulate a wide range of species, but not evergreen shrubs like creosotebush. Thus this study is the first attempt to simulate an evergreen shrub using ALMANAC. The developed plant parameters and plant growth curve were directly integrated into APEX model to simulate creosotebush and mesquite productions at a larger scale fields. The APEX model simulated water and soil qualities for each study site. In addition, APEX predicts the spatially distributed increase in water use by invasive creosotebush and mesquite within targeted watershed and also predicts effects of controlled and uncontrolled invasion on grass vegetation, water and soil conditions.

Parameters		**Description**
ALMANAC	**APEX**	
WA	WA	Biomass-energy ratio, g MJ^{-1} m^{-2}
HI	HI	Harvest Index
DMLA	DMLA	Max. leaf area index (LAI)
DLAI	DLAI	Fraction of season when LAI starts to decline
DLAP1	DLAP1	First point on optimal LAI curve
DLAP2	DLAP2	Second point on optimal LAI curve
PPL1	PPLP1	Plant population parameter (plants/100 m^2 for ALMANAC; plants/ha for APEX)
PPL2	PPLP2	Second plant population parameter (plants/100 m^2 for ALMANAC; plants/ha for APEX)
Tree1	Tree1	First point on multi-year S-curve function for tree LAI and height increase
Tree2	Tree2	Second point on multi-year S-curve function for tree LAI and height increase
CLAIYR	XMTU	No. years until maximum LAI
HMX	HMX	Max. crop height (m)
EXTINC	EXTINC	Extinction coefficient for calculating light interception
RTPRT1	RWPC1	Tree parameter, fraction of weight portioned to root for young plants.
RTPRT2	RWPC2	Tree parameter, fraction of weight portioned to root for plants near maturity.
PLANTPO	OPV5	Plant density (plants/100 m^2 for trees in ALMANAC; plants/ha for APEX)
PHU	OPV1	Potential heat use

Table 2. Plant parameters in ALMANAC and APEX adjusted for creosotebush and mesquite.

2.2.1. ALMANAC plant parameters and growth cycle development

2.2.1.1. Creosotebush

Based on field data, two types of creosotebush can be categorized based on crown size: CB1 (crown size <9098 cm2) and CB2 (crown size >9098 cm2). CB1 is mostly composed of younger, small, conical shaped shrubs, while CB2 is mostly composed of older, larger, hemispherical shaped shrubs. The growth patterns of CB1 and CB2 are visually distinct (**Figure 2a**). In years with adequate water, new tillers grow within CB1, and the conical shaped CB1 becomes the hemispherical shaped CB2 (**Figure 2b**) [51, 79]. Also, CB1 can reproduce either by seed (sexually) or clones (asexually). Biomass of creosotebush is dependent on the densities of CB1 and CB2, which vary among different topography features and climatic conditions. In the study sites, these two types of creosotebush co-exist at different densities (**Figure 2**).

In the ALMANAC Plants database, two separate sets of plant parameters named CB1 and CB2 were created for creosotebush (**Table 3**). Since creosotebush is a treelike shrub, growth of CB1 and CB2 were simulated as tree growth. The crop category number (IDC) was set as 7 (evergreen tree crop). Most parameters for plant growth (e.g. DMLA, DLAI, DLAP1, DLAP2, HMX, CLAIYR, and EXTINC) were derived from measured values [75]. The base temperature (TG, °C), the temperature below which development ceases, and optimum temperature (TB, °C), the temperature at which development rate and growth rate were greatest, were estimated from the observed weather data from the three weather stations. According to Fisher et al. [80] (1988) and Newingham et al. [81] (2012), creosotebush grows slowly in spring, while fast vegetative growth and reproductive growth occur in summer. Therefore, TB and TG for creosotebush were determined from average temperatures in spring and summer, respectively. For both CB1 and CB2 plant database, TG was set as 12°C, while TB was set as 25°C. PPL1, lower plant density (plants 100 m^{-2}) and fraction of maximum LAI at that density, and PPL2, higher plant density than PPL1 with fraction of the maximum LAI at that density, for CB1 were 10.01 and 35.03, respectively. PPL1 and PPL2 for CB2 were 2.20 and 11.85, respectively.

The ALMANAC code was modified to account for drought effects on development rate and for drought effects on plant stand. Creosotebush growth is largely affected by water availability. In addition, branch mortality of creosotebush increases as water deficit increases [26].

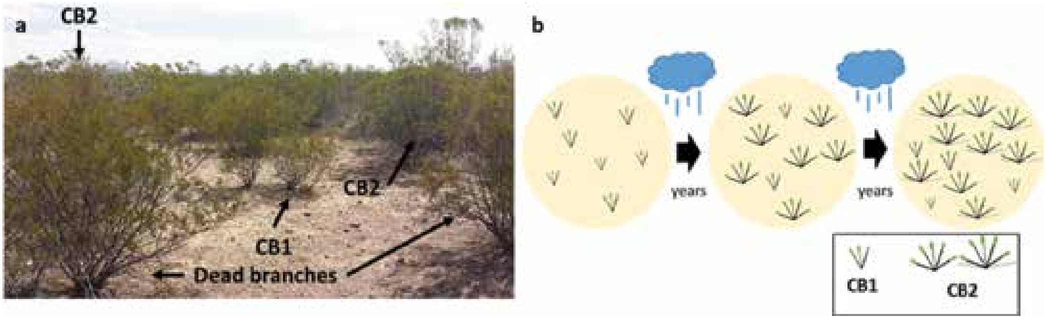

Figure 2. (a) Photograph of CB1 and CB2 growing in study area and (b) schematic description of formation of the patterns of creosotebush populations including CB1 and CB2.

Parameters	ALMANAC			APEX		
	Creosotebush			Creosotebush		
	CB1	CB2	Mesquite	CB1	CB2	Mesquite
WA	16.5	16.5	25	16.5	16.5	25
HI	0.01	0.01	0.76	0.01	0.01	0.76
DMLA	2.75	2.75	2.3	2.75	2.75	2.3
DLAI	0.93	0.93	0.9	0.93	0.93	0.9
DLAP1	41.88	41.88	15.3	41.88	41.88	15.3
DLAP2	92.98	92.88	60.7	92.98	92.88	60.7
PPL1	20.01	2.2	1.06	3500.03	1100.85	250.95
PPL2	35.03	11.85	25.95	2000.01	200.2	10.06
Tree1	40.03	40.03	50.07	40.03	40.03	50.07
Tree2	87.05	87.05	75.23	87.05	87.05	75.23
CLAIYR	20	20	3	20	20	3
HMX	1.7	1.7	1.8	1.7	1.7	1.8
EXTINC	1.32	1.32	0.38	1.32	1.32	0.38
RTPRT1	0.75	0.75	0.4	0.75	0.75	0.4
RTPRT2	0.3	0.3	0.3	0.3	0.3	0.3
PHU	2000	5000	1600	—	—	—

Table 3. Plant parameters in ALMANAC and APEX adjusted for creosotebush and mesquite.

In the modified code, degree days (potential heat units - PHU) that drive plant development do not accumulate when water stress is less than or equal to 0.4. Water stress is defined as the ratio of the soil water available for ET divided by the water demand for the day, based on PET and LAI. Thus plant development stops under such drought stress. In addition, when water stress is less than 0.2, the potential leaf area index (DMLA) (a surrogate for plant stand density) decreases by 1%. This accounts for reduced plant stand with severe drought. When there is sufficient water for no water stress (water stress = 1), DMLA is increased by 1% to account for increased tillering. DMLA is not allowed to exceed the input potential value for the plant.

To simulate the annual growth cycles of creosotebush, the model simulates growth over 2 cycles each year: between October and April/May (winter/spring) and between April/May and October (summer) [82]. Due to the overlapping sequence of growth among years, we created a series of 2 year growth cycles for creosotebush (**Figure 3**). In the first year of a 2 year growth cycle, LAI slowly increases during spring, reaches to maximum LAI during summer, and maintains the maximum LAI during winter. In the second year of the 2-year growth cycle, the simulated LAI slowly increases during spring, and then rapidly increases during summer.

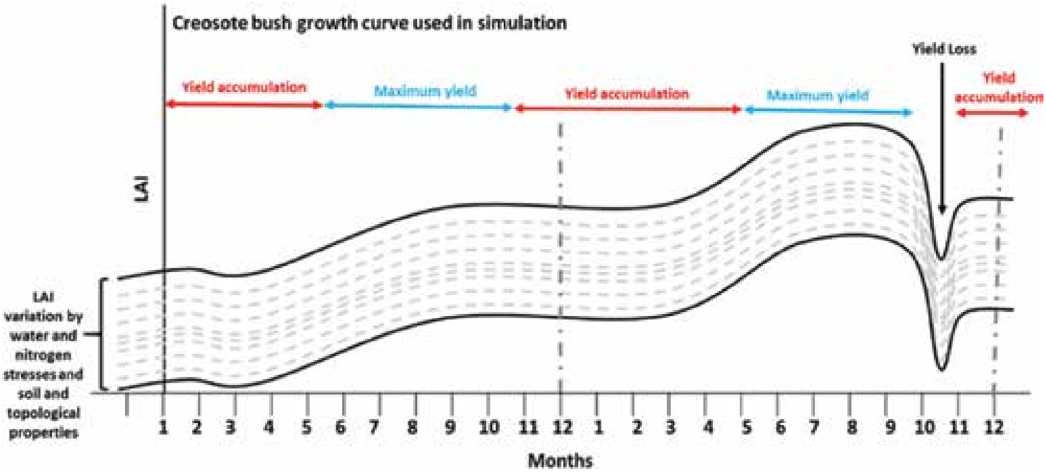

Figure 3. Conceptual creosotebush growth development in leaf area index (LAI) applied in ALMANAC simulation. The maximum LAI will occur in summer season and either maintain or decrease thereafter. The LAI varies depends on the total precipitation, nitrogen availability, and soil and topological properties. LAI variation is represented by the black solid and gray dash lines.

Twenty to fifty percent of aboveground biomass can be lost from plants every year, and the amount of this biomass loss depends upon the degree of habitat utilization by consumer organisms [83–85]. In addition, as the creosotebush grows older, its older branches gradually die and so the biomass may be reduced by decomposing dead older branches (**Figure 2**). Ludwig et al. [86] investigated creosote biomass in the growing seasons of 2 years and found that dead stem biomass was about half size of live stem biomass. According to Phillips and Comus [87], more than 60 species of insects are associated with creosotebush. Lac insects (*Tachardiella larrea*, a scale insect) are commonly found on stems and produce a lacquer-like substance by sucking juices out of the stem [87–90]. Termites, *Gnathamitermes tubiformans*, where they are abundant, have a significant impact on biomass loss of creosotebush. Termites consume mostly creosotebush leaf litter, especially older leaves, which apparently contain lower levels of antiherbivore allelochemics [91]. Johnson and Whitford [84] reported that termites annually consumed about 50% of the net primary production at a Chihuahuan Desert site.

In addition, the creosote grasshopper (*Bootettix argentatus*) lives on the plant and eats the small resinous leaves that creosotebush has developed to preserve water [87]. Mispagel [92] found that the grasshoppers consume from 0.8 to 1.9% of the cresosote bush's annual leaf biomass. Mammalian herbivores also consume great amount of the annual production [91]. For example, jackrabbits (*Lepus californicus*) eat leaves and stems of creosotebush [87]. Due to the factors listed above, though not measured directly in the study, it is expected that the annual creosotebush production is reduced between 20 and 50%. In the simulations, creosotebush biomass is reduced by removing 65% of its production without killing the plants in late October in the second year of 2-year growth cycle.

Since the plant stand densities of CB1 and CB2 varied among locations, the management parameter PLANTPOP (number of plants per 100 m^2) differed by location (**Table 4**). Among the 13 sites sampled in the previous study [75], 12 sites were included in this study. "Alpine A" site was removed from this study due to small sample size. Values of PLANTPOP of CB1 and CB2 were determined based on the measured densities reported in Kim et al. [75]. Since creosotebush does not drop all leaves after maturity, large values of potential heat units (PHU) were assigned for CB1 and CB2 at all locations. The value of PHU should be close to the number of growing degree days for the area and should be large enough to avoid a terminating harvest operation in the simulations. The PHU values of 2000 and 5000 were used for CB1 and CB2, respectively, grown over the 2-year growth cycle at all sampling locations. A similar large value of PHU was also used in simulations of 2- year growth cycle sugarcane yields (*Saccharum officinarum* L.) in Hawaii [93].

After the initial year of establishment, the 2 year growth cycle was repeated within growth periods of creosotebush, and then 85% of biomass was harvested on the harvest date (February 1). Creosotebush is a slow-growing shrub that takes approximately 6 and 12 years to become CB1 and CB2, respectively [75]. Thus, the growth period or the number of years of simulation (NBYR) should be in the range of 6 and 12 years. Based on the field data, mean number of growth rings for CB1 and CB2 was used as the growth period or the NBYR for each site. Two more sets of tree plant parameters were used in the simulation: Tree1 and Tree2 (**Table 1**). In Tree1 and Tree2, the numbers before decimal are % of period between planting and maturity. The numbers after decimal were derived from slope of relationship between LAI and height. Values of Tree1 and Tree2 were 40.03 and 87.05, respectively, for both CB1 and CB2.

Site ID	Mean	PLANTPOP		Measured yield[a]	ALMANAC simulated yield
		Plant density (plants 100 m^{-2})			
	year	CB1	CB2	Mg ha^{-1}	Mg ha^{-1}
Fort Stockton 1	12	4	4	0.84	0.84
Fort Stockton 2	9	18	13	2.81	2.62
Fort Stockton 3	9	13	8	1.70	1.62
Alpine 1	11	7	14	2.60	2.57
Alpine 2	7	26	6	1.77	1.7
Alpine 3	8	29	10	2.53	2.5
Alpine 4	6	14	0	0.39	0.35
Alpine 5	7	34	0	0.94	0.73
Alpine 6	6	29	2	1.18	0.98
Alpine 7	7	21	0	0.58	0.73
Alpine 8	9	12	18	3.47	2.68
Alpine 9	7	17	9	1.96	1.99

[a]Measured yields were obtained from Kim et al. [75].

Table 4. Number of years for different simulation operations, plant density of CB1 and CB2, measured yields, and ALMANAC simulated yields for 2016 at all samples collected locations.

2.2.1.2. Honey mesquite

Honey mesquite is a winter-deciduous tree or shrub. Growth of mesquite was simulated as tree growth. The plant category number (IDC) was set as 8 (deciduous tree plant). Most parameters for biomass-energy ratio (WA), and plant growth (e.g. DMLA, DLAI, DLAP1, DLAP2, HMX, CLAIYR, and EXTINC) were derived from measured values [76] (**Table 3**). Other plant parameters were derived from previously published research, and the ALMANAC model's database of over 100 plant species' parameters, with minimal adjustment after comparing output with measured tree biomass data. The base temperature (TG, °C), the temperature below which development ceases and optimum temperature (TB, °C), the temperature at which development rate and growth rate were greatest were obtained from literature reviews. Mesquite seedlings produce the highest biomass yields at 27°C [94]. Mesquite begins to leaf out least in April, increased until July [95]. So, the TG for mesquite was determined from average minimum temperature in April. For mesquite database, TG was set as 15°C, while TB was set as 27°C. Parameters FRST1and FRST2 indicate two points on the frost damage curve. Numbers before decimal are the minimum temperatures (C) and numbers after decimal are the fraction of biomass lost each day the specified minimum temperature occurs. According to Schuch and Kelly [96], mesquite can survive temperature down to −18°C, thus FRST1, was set to 18.3, while TB was set to 20.99. Ansley et al. [35] reported that the root-to-shoot mass ratio is 0.32 for mesquite grown under control (plants only obtained water from precipitation). A similar result was also observed in Kiniry [76] who reported root-total biomass ratio was 0.38. Based on these results, RTPRT1 and RTPRT2 were set as 0.4 and 0.3, respectively. The values of potential heat units, PHU, should be close to the number of growing degree days for the area and should be large enough to avoid growth stoppage before normal maturity date in the simulations. The PHU values for mesquite shrub were 1500. The heat units were accumulated annually and reset to 0 at the end of each year. The growth cycles for mesquite were created. Based on the field experimental design, mesquite seedling planted 1 m apart, so the mesquite plant density was set as 100 per 100 m^2. We assumed trees became established 20 March in the first year, and plants were killed after harvest on 20 September in the final year of a simulation. The growth period or number of years of simulation (NBYR) varied from 2 to 4 years from establishment.

2.2.1.3. ALMANAC calibration and validation

To evaluate the plant parameters and test ALMANAC's ability to accurately simulated creosotebush biomass, simulated biomass values were compared with the measured biomass values from field measurements by estimating correlation and linear regression. Creosotebush simulated yields in 2016 were compared with measured yields across 12 sites [75]. For mesquite, measured values of LAI collected from May, June, July, and September in 1995 were reported by Kiniry et al. [76]. Simulated values of LAI in May, June, July, and September in 1995 were compared with the measured LAI by estimating correlation and linear regression. Simulated biomass values in September 1993–1995 were compared with the measured biomass values from field measurements [76]. Relative ratio between simulated and measured dry biomass yields were calculated in each year.

2.2.2. APEX simulation development

United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) has conducted to detailed surveys of soils, geomorphology, and vegetation communities at O2 Ranch located in Brewster County, TX. Based on the report [46], creosotebush and mesquite were commonly found in the O2 Ranch. The creosotebush field study was conducted on the same ranch. Thus, the Alpine study site was used for APEX simulation (**Table 1** and **Figure 4**). The suitability of soils for most kinds of field crops in Brewster County are divided into three groups: Capability Class (CC) VI, VII, and VIII [77]. Most areas in O2 Ranch are classified as CC VI that contains soils having severe limitations that make them generally unsuitable for cultivation and that restrict their use mainly to pasture, rangeland, forestland, or wildlife habitat [46]. The projecting areas where vegetation simulation occurred are flatter and gently sloping between 0.5–1% (tangent multiplied by 100) slope terrain on the O2 Ranch [46]. Through APEX application, shrub productivity was simulated at all study subareas with different topographic features and climate conditions of small-scaled watershed in O2 Ranch in western Texas (**Figure 5**). APEX performs these processes across channel systems to the outlet of a field through channels, subsurface flow, or ground water [46, 97]. The first step in APEX model setup was to divide a small watershed or field into smaller spatial units called subareas (sub-watershed) represented with homogenous soils and topographic properties. Digital Elevation Model (DEM) was used in ArcAPEX to create the channel network in the study watershed, which was then used for describing the APEX routing scheme from one subarea to another and to the watershed outlet (**Figure 5**). A DEM layer in 10-meter grids was downloaded for the study sites from USDA-NRCS: Geospatial Data Gateway [98]. The DEM was processed and reprojected using ArcGIS version 10.2.2.3552.

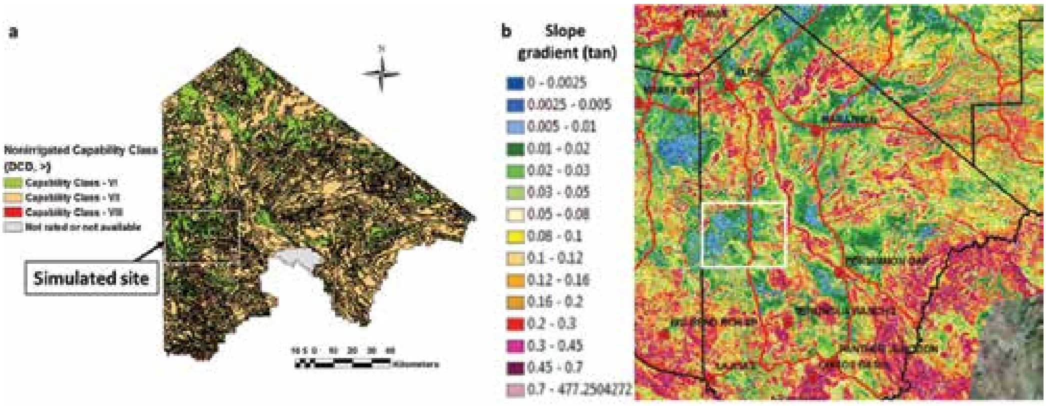

Figure 4. Maps of Brewster County, TX showing (a) non-irrigated capability class and (b) slope gradient. Non-irrigated capability class is defined as the suitability of soils for most kinds of field crops. The soils are grouped into three classes: VI, soils have severe limitations that make them generally unsuitable for cultivation and that restrict their use mainly to pasture, rangeland, forestland, or wildlife habitat; VII, soils have very severe limitations that make them unsuitable for cultivation and that restrict their use mainly to grazing, forestland, or wildlife habitat; VIII, soils and miscellaneous areas have limitations that preclude commercial plant production and that restrict their use to recreational purposes, wildlife habitat, watershed, or esthetic purposes [77]. Map of slope gradient was obtained from PSSAT [46].

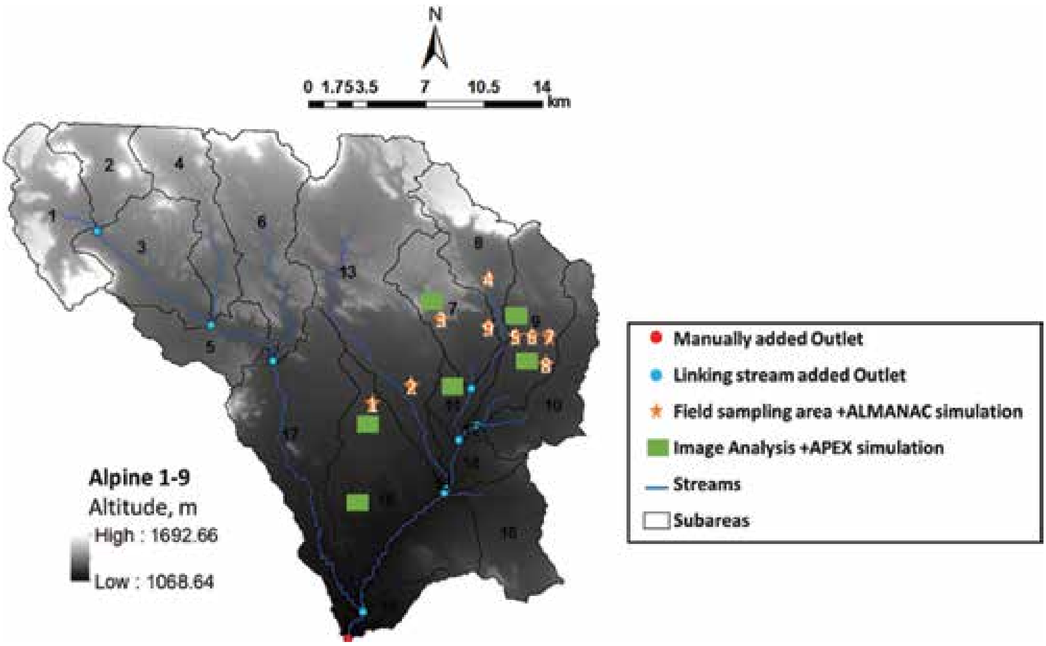

Figure 5. Stream network and the associated APEX subwatersheds (subareas) delineated from 10 m digital elevation models (DEMs) for all study locations. Numbers in subareas indicate subarea ID numbers input by user.

A small field in Alpine had the highest elevation range (1063–1699 m) (**Figure 5**). In Alpine, 19 subareas were created within a watershed, but only five subareas (Subarea ID: 7, 8, 9, 13, 18) were used for field morphological collection. After subareas were delineated, the land use/land cover, soils, and slope distributions were characterized for each subarea. The United States land use map was downloaded from the USDA-NRCS: Geospatial Data Gateway. The land use layer was processed and reprojected using ArcGIS version 10.2.2.3552. The soil data layer was imported from the U.S. SWAT2012 SSURGO soils database which is packaged and integrated with the ArcAPEX interface. The dominant soils in the five study subwatersheds in Alpine were gravelly loamy and bedrock soils. The dominant soils in the subwatersheds for Fort Stockton 1–3 were gravelly loam and loam. The historical weather data used in the ALMANAC model was reformatted and used for APEX simulation.

2.2.2.1. *APEX calibration and validation*

APEX was calibrated and validated with satellite image analysis from Subareas 7, 9, 11, and 18. Satellite image analyses of quantifying creosotebush canopy cover (density) in four study sites were performed using Texas Natural Resources Information System (TNRIS) (available at https://tnris.org/data-download/#!/quad/) and ImageJ (available at https://imagej.nih.gov/ij/index.html). The TNRIS provided historical satellite images of the six sites within Subareas 7, 9, 11, and 18 between 1996 and 2016 (**Figure 5**). Satellite images that were taken between January and February were used because only creosotebush has green leaves during the winter. January and February satellite images are only available in 1996 and 2015. The size of captured area conducted to quantify plant canopy cover varies between study sites due to various topography features at the four study sites. The total areas used for quantifying plant canopy cover were between 0.73 and 5.94 km^2. The captured satellite image was converted to 16-bit grayscale image using ImageJ (**Figure 6**), and the density of creosotebush was measured by quantifying the fraction of gray values over the entire image. The detail method is described in ImageJ manual (available in https://imagej.nih.gov/ij/docs/menus/image.html).

APEX simulated creosotebush yields in 1996 and 2015. All study subareas were configured with the same management inputs as in the ALMANAC model. Plant parameters for creosotebush and mesquite are described in **Table 1**. Plant parameters were transferred from the plant database in ALMANAC, except for PPL1, PPL2, COSD, PRY, EXTINC, and PHU. In APEX model, plant population parameter is in different units from ALMANAC. In APEX, the plant population parameter is expressed in number of plants per hectare, and PPLP1 should be larger than PPLP2 for tree crops. In addition, the extinction coefficient for calculating light interception is a fixed number, 0.65, which is the representative of crops with narrow row spacing [99]. APEX calculates PHU from time from planting to maturity (XMTU). Since the plant stand densities of CB1 and CB2 varied among locations, the management parameter PLANTPO (number of plants per hectare) differed by subareas (**Table 3**). When more than one sampling site was in one subarea, average density of each CB1 and CB2 calculated from sampling sites were used. The growth period or number of years of simulation (NBYR) for each subarea was 25 years from establishment (1992–2016). The growth cycle management was followed by the 2-year growth cycle. The average ratio of simulated 2015 and 1996 yields in each subarea were compared with ratio of density of 2015 and 1996 by estimating correlation and linear regression.

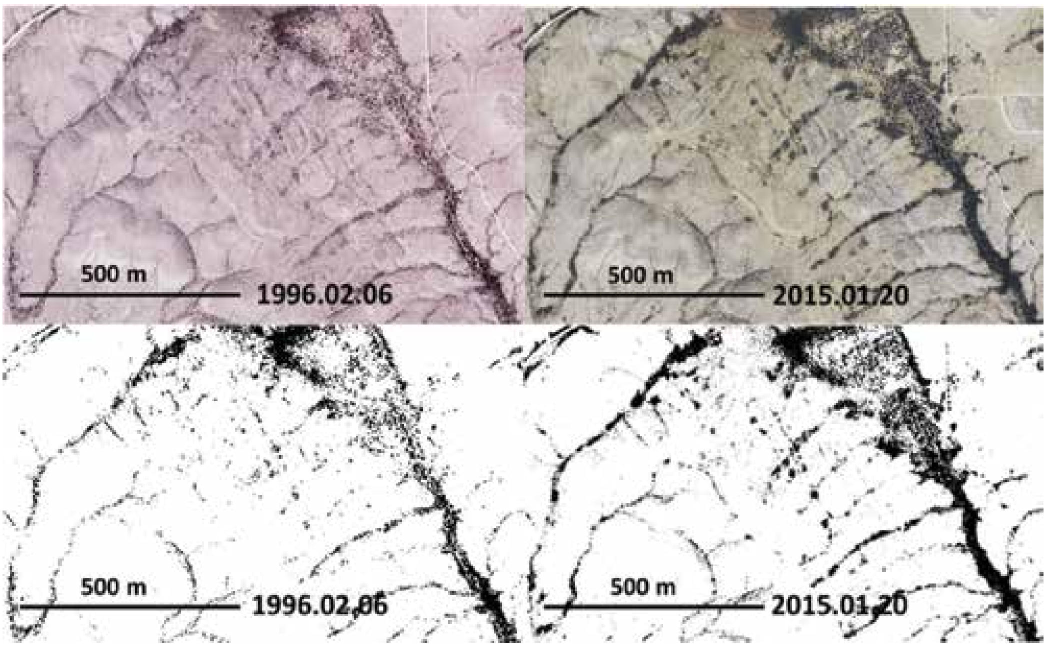

Figure 6. Satellite and greyscale images of creosotebush population density distribution in Subarea 11. Images are from either January or February in 1996 and 2015. Creosotebush population is shown as green and black dots in satellite and greyscale images, respectively.

2.2.3. APEX simulation on effects of invasive control

Each subarea is relatively homogeneous in terms of soil, land use, management, and weather. In addition, the effects of invasive shrub control on vegetation and soil and water quality were evaluated. The invasive shrub-perennial grass competitive interactions were evaluated by simulating quantitatively changes in yield, soil organic carbon in plow depth in kg/ha (OCPD) and soil water content (SW) when only shrub grows, when only mixed perennial grasses grow, or when shrub and mix perennial grass grow together. Plant parameters for creosotebush and mesquite are described in **Table 3**. The same plant parameters and management for mixed perennial grasses (black grama, blue grama, and sideoat grama) were obtained from ALMANAC model that were already developed from plant data set collected in Texas [70, 100]. Management for mixed perennial grasses in first simulated year consisted of fertilizer application on 1 April, planting in 50 plants m^{-2} for each grama on 10 April, and harvesting on 30 October. All black, blue, and sideoat gramas had 1800 PHUs. The simulation years for perennial grasses were same as shrub ages observed in the subareas. In addition, APEX quantitatively evaluated soil erosion, sediment yield, and water stress (days) when only shrubs grow, when only mixed perennial grasses grow, or when shrubs and mixed perennial grass grow together in all study subareas. Surface runoff (Q) was calculated using the modified Soil Conservation Service (SCS) curve number (CN) technique [101]. The SCS runoff CN can be adjusted by soil type, land use, land slope, soil water content and management practices. The CN and given daily rainfall value were used as inputs to compute soil erosion (RUS2) in each study subareas [99]. The average sediment concentration (CYAV) values were also calculated for all subareas through APEX simulation.

3. Results and discussion

3.1. ALMANAC model yield simulation and validation

3.1.1. Creosotebush

Based on the growth patterns of creosotebush obtained from field measurements and the literature, a two-year growth cycle model was created. Results show that the LAI values for CB1 and CB2 gradually increase during spring, reach maximum LAIs during summer, and maintain the maximum LAIs during winter within the first year of the two-year growth cycle. In the following year, LAIs from the previous year gradually increase during spring, reach maximum LAIs during summer, decrease in late October, and slowly regrow during winter (**Figure 3**).

The simulated dry biomass yields of creosotebush were compared with the observed biomass yield from 12 study sites (**Table 4**). Various sizes and ages of creosotebush plants were found in different densities across 12 study sites. The biomass yields also varied across the sites and were mainly due to total shrub density and proportion of CB2 shrubs within the area. The greatest measured and simulated yields were observed in Alpine 8, which has 3.47 Mg ha^{-1} and 2.68 Mg/ha, respectively. The lowest measured and simulated yields were observed in Alpine 4, where the shrub density was 14 per 100 m^2 and only had CB1 shrubs. The r^2 between simulated and measured values for dry aboveground biomass based on the 1:1 line was 0.95. These values indicate that the model performed well (**Figure 7**).

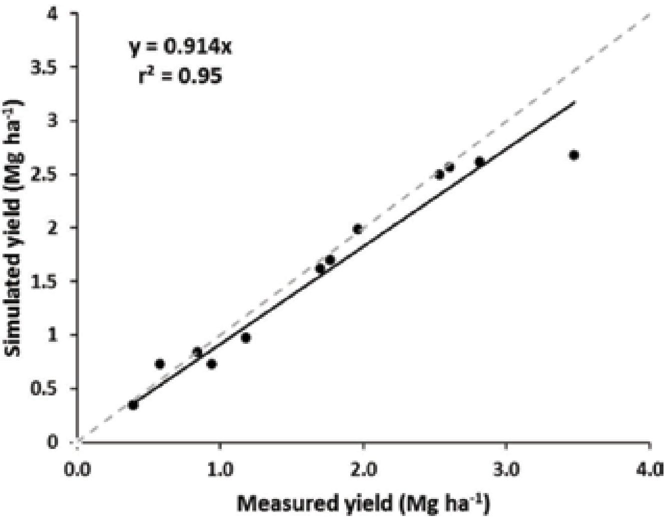

Figure 7. Comparison of measured biomass yields and ALMANAC simulated biomass yields of combined two creosotebush populations including CB1 and CB2 at all study locations.

3.1.2. Honey mesquite

Honey mesquite is a winter-deciduous tree that drops its leaves in winter and leafs out again in late March or early April [96]. Simulated LAI values for honey mesquite gradually increase during spring, reach maximum LAIs during summer, and decrease in mid-October (**Figure 8a**). Each year shows a similar LAI developmental pattern, but the maximum LAI increases as tree age increases (**Figure 6a**). The simulated LAI values at the main development stages (May to September in 1995) were realistically simulated, with a highly significant fit ($r^2 = 0.94$) (**Figure 8b**).The simulated dry biomass yields of honey mesquite were compared with the observed biomass yields from Kiniry [76]. As LAI increased from 1993 to 1995 (**Figure 8**), the measured and simulated mesquite dry yields increased from 1993

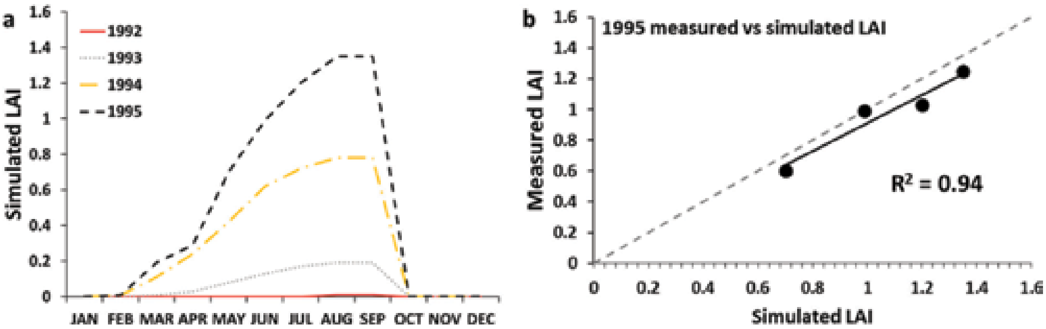

Figure 8. (a) ALMANAC model simulated leaf area index (LAI) developmental curves in 1992–1995 and (b) comparison between measured and simulated LAI values in may, June, July, and September in 1995. Measured LAI values were obtained from Kiniry [75].

to 1995 (**Table 5**). The simulated dry yield production agreed well with measured yields of mesquite in 1993–1995 (**Table 5**). Relative ratios between simulated and measured dry biomass yields in 1993–1995 were obtained between 0.91–1.11.

3.2. APEX calibration and validation

The APEX model was validated by comparison of the simulated biomass yield pattern between 1996 and 2015 with real satellite imagery (**Table 6**). According to Kim et al. [75] creosotebush size and leaf area index were highly correlated with aboveground biomass yield (both $r > 0.8$). Thus, spatial patterns in canopy cover may directly reflect changes in yields since the study area is dominated by creosotebush. The APEX aboveground biomass yield changes between 1996 and 2015 agrees relatively well with creosotebush canopy cover ($r^2 = 0.61$) (**Figure 9**).

Both canopy cover and simulated above ground biomass yield increased between 1996 and 2015 in all subareas. The highest increases in yield and canopy cover were observed in Subarea 7 (**Table 6**). Based on map of watershed (**Figure 5**), Subarea 7 was at higher altitude and may have much steeper slope areas. This may be why fewer creosotebush established in Subarea 7 in 1996. But, after establishing, creosotebush production may have exponentially increased by producing new tillers within clones in 2015. However, the canopy cover estimation (% km^{-2}) and simulated biomass yield (Mg ha^{-1}) has a weak relationship ($r^2 = 0.19$) (**Figure 9**). This may be because the study areas may have high topographic variation [102, 103], or surface features (e.g. exposed rock and soil) which can create mixed pixels in satellite data [104]. Moreover, the size of satellite images is much smaller than simulating subareas, which can further confound the relationship with biomass.

3.3. Modeling the potential effects of control of invasive plants

Through APEX, effects of invasive shrub control on mix perennial production, soil organic, and water content were calculated when only invasive shrubs (creosotebush and mesquite) grow, when only mixed perennial grasses grow, or when they grow together in Alpine subareas. In APEX, the surface runoff was calculated to predict soil erosion and sediment concentration in channelized flows. Annual average values of these simulation results were summarized in **Table 5** for 25-year simulation period (1992–2016). Subarea 7 had highest soil erosion, while

Harvest year	Canopy area per tree (m^2)[a]	Measured yield (Mg ha^{-1})[a]	Simulated yield Mg ha^{-1}	Measured/simulated
1993	1	0.89	0.91	0.98
1994	1	4.54	4.97	0.91
1995	1.37	12.46	11.24	1.11

[a]Source adapted from Kiniry [76].

Table 5. The harvest year, canopy area per a tree, measured dry biomass yield (Mg ha^{-1}), simulated dry biomass yield (Mg ha^{-1}), and relative ratio between measured and simulated dry biomass yields of mesquite in 1993, 1994, and 1995 at Temple, TX.

APEXSubarea	Area of subarea	Imagery analysis					APEX simulation				
			Creosotebush cover (%)		2015/1996	Avg.	Plant density (plants ha^{-1})		Creosotebush biomass yield (Mg ha^{-1})		2015/1996
ID	ha	Rep	1996	2015		2015/1996	CB1	CB2	1996	2015	
7	2907	1	2.90	11.10	3.8	3.8	2900	1000	0.55	2.73	5.0
9	9575	1	8.03	17.71	2.2	1.9	2400	500	2.19	3.99	1.8
		2	8.59	14.14	1.6						
11	930	2	7.04	10.01	1.4	1.4	2300	1000	3.01	4.40	1.5
18	7180	1	3.17	10.56	3.3	2.9	700	1400	3.09	4.51	1.5
		2	1.70	4.18	2.5						

Table 6. APEX subarea ID, subarea size, creosotebush canopy cover (%) per km^2 from satellite imagery, ratio of canopy cover between 2015 and 1996, ratio of canopy cover averaged within subarea, plant densities of CB1 and CB2, wet yield (Mg ha^{-1}), and ratio of yield between 2015 and 1996.

Subareas 9, 11, and 18 had same soil erosion. When only perennial grasses (black-, blue-, and sideoat gramas) were planted, soil erosion increased. This is may be because perennial grasses have different root structures from creosotebush and mesquite. Vegetation roots were of substantial importance for soil reinforcement. Although perennial grasses have intense small roots that contribute more strength per unit area than the larger roots of creosotebush and mesquite [105], relative low vegetation cover, results in decreased root coverage per area, may increase soil erosion (**Table 7**). The perennial grass yield was relatively low due to high water stress days (**Table 7**). Under irrigation, mixtures of black-, blue-, and sideoat gramas can potentially produce 7 Mg ha^{-1} [100].

When only perennial grasses were planted, the sediment yield increased as soil erosion increased. Soil water content decreased when shrubs and perennial grasses grew together (**Figure 10**), which led to high numbers of water stress days (**Table 7**). Since perennial grasses suffer water stress, productivity of perennial grasses when subjected to competition with shrubs is lower than perennial biomass yields with no competition. Among four subareas, Subarea 7 had the lowest perennial grass productivity due to high values of soil erosion and

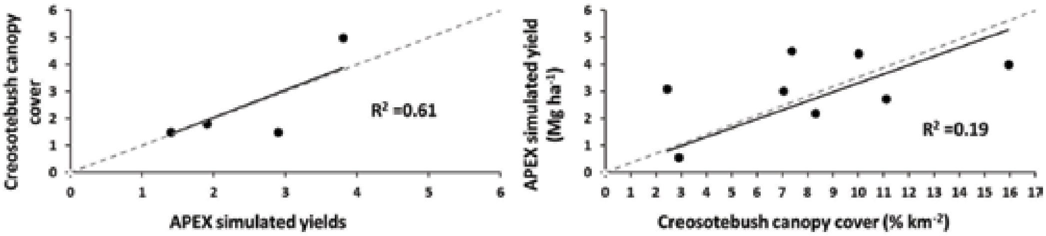

Figure 9. Comparison of (a) the patterns of simulated biomass yield and estimated canopy cover from satellite imagery between 1996 and 2015 and (b) simulated biomass yields and estimated canopy cover from satellite imagery.

Subarea ID	Soil erosion (Mg ha^{-1})			Sediment yield (Mg ha^{-1})			Water stress (days)			Perennial grasses simulated yield (dry Mg ha^{-1})	
	S	P	SP	S	P	SP	S	P	SP	P	SP
Sub 7	0.017	0.249	0.006	0	0.023	0	480	522	1205	0.907	0.166
Sub 9	0.001	0.090	0.001	0	0.004	0	336	458	1114	1.189	0.448
Sub 11	0.001	0.016	0	0	0.001	0	330	464	1110	1.199	0.287
Sub 18	0.001	0.054	0	0	0.002	0	333	471	1123	1.196	0.246

S indicates the simulated values when only invasive shrubs (creosotebush and mesquite) were planted; P indicates the simulated values when only perennial grasses (black-, blue-, and sideoat gramas) were planted; and SP indicates the simulated values when shrubs and perennial grasses.

Table 7. APEX subarea ID and annual averages of surface runoff, soil erosion, sediment yield, and water stress days for APEX subwatersheds (subareas) that were used in this study.

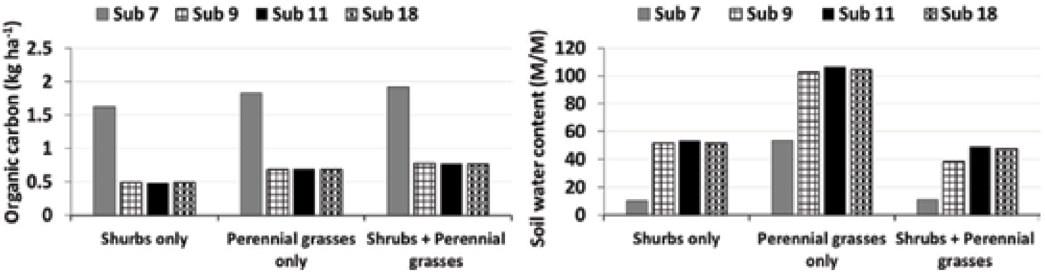

Figure 10. APEX simulated organic carbon yield (kg ha^{-1}) in plow depth and soil water content (M/M) when only invasive shrubs (creosotebush and mesquite) were planted, when only perennial grasses (black-, blue-, and sideoat gramas) were planted, and when shrubs and perennial grasses in APEX subarea 7, 9, 11, and 18 in 2016.

water stress days. Increased perennial grass density resulted in increased soil organic carbon stocks (**Figure 10**). Soil organic carbon yield also increased when perennial grasses and shrubs grew together (**Figure 10**).

4. Summary and conclusion

Overall, the modeling results reveal that the combined approach with ALMANAC and APEX is capable of accurately simulating the productivity of creosotebush and mesquite. Both models are capable of simulating variability of shrub yields depending on water availability. For example, the shrub yields from eroded soils are lower than those from uneroded lands. With developed plant parameters and growth cycle, APEX model is capable of simulating the effects of invasive shrubs on vegetation and soil and water qualities in different topological conditions. As shrub density decreases, the perennial grass richness, organic carbon yield, and water contents increase. However, the perennial grass mixtures with black-, blue-, and sideoat gramas show low productivity in arid regions due to high water stress levels. Further studies are necessary to conduct a series of simulation studies to demonstrate productivity of diverse native perennial grasses in the rangelands. Identification of perennial grasses that are well adapted to desert arid rangeland is essential process to determine the best management strategies for these lands. This modeling approach developed in this study can provide a realistic decision making tool that can predict results of various rangeland management strategies, which will optimize management strategies.

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Section 3

Climate Hazards

Chapter 3

Farmers' Vulnerability to Climate Change Impacts in Semi-arid Environments in Tanzania: A Gender Perspective

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Additional information is available at the end of the chapter

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Abstract

This chapter reports on the study conducted in semi-arid environment in Iramba and Meatu districts to examine gender vulnerability and adaptations to climate change impacts. The study adopted qualitative approach that brought together smallholder farmers and agro-pastoralists to discuss issues, in nine focus group discussions, in three villages. A total of 99 participants were involved. The results showed that the major climatic hazards since 1985 were, among others, drought, floods, strong wind accompanied with "ice falling," and crop and livestock diseases including malaria and cholera that affected humans. Their frequencies were reported to be on the increase, especially since the 2000s. Such hazards negatively affected livelihoods resources like land, livestock, human and water resource that in turn affected communities' livelihoods. Men and women had developed different coping and adaptation strategies, which had not changed much in the past 30 years. Men's strategies were related to mobility contrary to women counterparts. The chapter concludes that women and children were more vulnerable due to factors like limited control over livelihoods resources, limited mobility, domestic chores and the general subordinate position in the communities. Concerted integrated programmes from various stakeholders are required to rectify an existing situation.

Keywords: vulnerability trends, climate change, community livelihoods

1. Introduction

In Tanzania, vulnerability to climate change impact jeopardizes development efforts through directing available resources to reducing or curbing short-term and long-term impacts. The body of literature on climate change has increased considerably since the 2000. Some writers including Nombo et al. [1] have reported climate change impacts that are differentiated by gender. However, gender vulnerability is not sufficiently explored. The concept of vulnerability to climate change is viewed to include outcome vulnerability that connotes outcome of climate change impacts as adopted in this chapter. It is also taken as contextual vulnerability that is a response of climate – society interactions [2]. In view of the outcome vulnerability, scholars consider the outcome of exposure to the stimuli, sensitivity and adaptive capacity [3, 4]. Others take vulnerability to climate change impacts as a degree to which one is susceptible to the negative impacts or the extent to which climate change damage or harm a system [5]. In line to this understanding, the author of this chapter contend that when adaptive capacity is low and when coping and adaptation strategies to climate change impacts are not working effectively due to gender inequality, among other factors, the phenomenon compromises livelihoods resources and community livelihoods, more generally.

Literature demonstrates different models of disaster risks that are used to assess vulnerability including, among others, pressure and release and access model [6] and CARE International climate vulnerability and capacity analysis model. The CARE's model helps to understand implications of climate change for community livelihoods, including identification of the most vulnerable social groups that capture dimensions of local adaptation and coping strategies [7]. To that effect, this model is suitable for analyzing vulnerability with a gender perspective. The pressure and release model views vulnerability as a progression from root causes, to the processes or activities that transform the root causes into particular forms of insecurity and finally into unsafe conditions. Root causes include limited access to power, structures and resources. They also include limited access to political and economic systems. It appears that, although some models like the CARE's model put gender as an "add on" component; existing vulnerability to climate change models are gender blind.

It is worth noting that vulnerability assessment is vital for households and communities whose livelihoods depend on natural resources that are sensitive to climate change impacts. Since gender dimension is critical for development, vulnerability assessment with a gender lens is also critical because gender inequality is prominent in Sub-Saharan Africa (SSA) and particularly in Tanzania relative to other regions in the world [8]. Literature shows that community livelihoods in semi-arid environments, like in Iramba and Meatu in Tanzania, are more at risk of being affected by climate change impacts because of high dependence on rain-fed crop production and livestock keeping, which are both sensitive to the phenomenon [9, 10].

Smallholder farmers and agro-pastoralists in semi-arid environments in developing countries like Tanzania are characterized by poor living conditions manifested through low household income, food insecurity, inadequate health services, unstable energy supplies, and fragile natural ecosystem. This prevailing condition exacerbates farmers and agro-pastoralists' vulnerability to the climate change impacts [7, 11]. As such, there is a growing concern that women are more vulnerable to the impact relative to men counterparts because of unequal gender relations, which tend to downgrade women in the sphere of access to and control over resources that can assist coping and adaptation measures [1, 8, 11, 12]. Women exclusion in decision-making and planning for adaptation measures may exacerbate the problem [11, 13, 14].

This chapter acknowledges the fact that women are "agents of change" for designing gender sensitive adaptation policies to address climate change impacts, thus reducing gender vulnerability [15]. However, available studies on vulnerability to climate change impacts including Kelly and Adger [5], O'brien et al. [2] and Coletti et al. [3] do not address gender dimension squarely from methodological point of view to the outcomes. This information is critical because different gender groups have different adaptation and coping strategies and also different ability to adapt to climate change impacts, hence different vulnerability. For instance, while men consider migration as a strategy to reduce vulnerability, it is likely to increase vulnerability among women who have limited mobility particularly in rural communities [16].

1.1. Analytical framework

The key concepts in this chapter are: gender vulnerability, climate change and livelihoods. A concept like climate change is seriously conceptualized in the literature as a long-term mean statistics of weather [4, 9]. This study takes climate change as any long-term change in rainfall and extreme weather events like drought and floods. In addition, livelihood is conceptualized in this chapter to include possession of human capabilities like education, skills and health; access to tangible and intangible assets and existence of economic activities [17, 18]. The concept is essentially about how different people in a community live, what resources do they depend and what activities do they undertake to sustain their living. Gender vulnerability, therefore, considers complex relations between men and women in a community and how these relations result into unequal vulnerability between men, women and children [14].

This chapter puts livelihoods at the center of the communities to understand how people live and what resources and activities do their livelihoods depend. It picks some elements of the CARE's model [7] named as CAREs' climate vulnerability and capacity analysis model. This helps to understand implications of climate change impacts on community livelihoods, and also helps to identify the most vulnerable social groups including dimensions of local adaptation, which involve anticipating, planning and acting to reduce vulnerability; and coping strategies, which involve the use of available skills, resources and opportunities to address, manage and overcome short-and medium-term vulnerability, though can, in the long-term increase vulnerability [7, 19].

The chapter adopts some elements of the Sustainable Livelihood Approach (SLA) developed by DFID [20] in understanding how livelihoods assets and outcomes are affected by the vulnerability context like shocks, trends and seasonality of climatic and non-climatic hazards. The livelihoods assets include human, social, financial, natural and physical capital, which when negatively affected by vulnerability hazards translates into increasing community vulnerability by affecting food security, income, and natural resource base, hereunder also named livelihoods resources like land and water. The analysis of community vulnerability, with a gender lens, due to the long-term climate change impacts and other stressors in the context of SLA assist answering questions like "how community livelihoods, men and women, are affected by climatic and non-climatic hazards, which forms the vulnerability context of the livelihoods assets." The analysis also explores gender differential vulnerability by looking at types of coping strategies and ability of men and women to cope or adapt to the climate change impacts.

2. Study areas

The study was conducted in Iramba and Meatu districts. Iramba is found in Singida while Meatu is found in Simiyu Region. Both districts lie entirely in semi-arid environments, which are prone to droughts and other manifestations of climate change. The districts were selected for the study because poverty, defined as the inability to meet a minimum standard of living, is as high as 80% [1] suggesting that the districts were likely to be vulnerable to the climate change impacts [4, 7]. Being contiguous, the two districts were good for assessing differences in terms of manifestation of climate change and gender vulnerability to the phenomenon for the two communities: the Wasukuma in Meatu and the Wanyiramba in Iramba.

The mean annual rainfall in Meatu ranges between 400 mm and 900 mm in the southern and northern parts respectively [21]. In Iramba, the mean annual rainfall ranges between 500 mm and 850 mm and the surface temperature ranges between 15°C in July and 30°C in October [22]. The rainfall regime in both districts is unimodal, which starts in November and ends in April [23]. In Meatu, vegetation is mostly shrub and thorny trees scattered or clustered in some parts while Iramba's vegetation include Miombo woodlands, acacia woodlands and grasslands [24]. Three villages were involved in the study: Mwamanimba and Mwashata in Meatu and Kidaru in Iramba. The two villages in Meatu are dominated by the Sukuma while Kidaru in Iramba is dominated by the nyiramba. All villages in the study areas are dominated by the smallholder farmers. Mwamanimba is dominated more by agro-pastoralists whose livelihoods rely on rainfall. This means that any change in rainfall is likely to affect livelihoods. Since smallholder farmers and agro-pastoralists are poor in the study areas [1], it was anticipated that they are likely to be vulnerable to climate change impacts.

3. Methodology

This chapter adopts qualitative approach to research as emphasized by Chambers [25] and Creswell [26]. Data were collected from smallholder farmers and agro-pastoralists using focus group discussions (FGDs). **Table 1** shows villages, number of FGDs, their size [27] and age of participants involved. There were separate groups for men, women and youth for each tool used to collect data in each village to get insights from different gender groups. The United Republic of Tanzania (URT) in its National Policy of Youth Development [28] defines youth as those whose age is within a range of 15–35 years. During FGDs, the study employed historical time line to assess trends and frequencies of vulnerability hazards related to climate change and those that are non-climatic hazards. Three time lines were established, one for each gender group: men, women and youth. This method also helped to get insights about past hazards and their changes in the previous 30 years since 1985. It also helped men and women to make sense of the trends of the hazards and changes over time. Special attention was given to major hazards and their effects, changes in land use and land cover, changes in food security and major political events like local governments and national elections. Adaptation and coping strategies, their changes and effectiveness, were also assessed.

Secondly, the study used seasonal calendar to identify periods of stress, famine and vulnerability, to understand livelihoods and coping strategies, to analyze changes in seasonal activities, and to evaluate how vulnerability varied seasonally between men and women. Other

Village name	Number of FGDs conducted	Number of men participants	Number of women participants	Number of youth participants	Mean age (years)	Minimum age (years)	Maximum age (years)
Kidaru	3	11	12	11	49	30	75
Mwashata	3	12	10	12	54	39	76
Mwamanimba	3	10	10	11	44	20	73
Total	9	33	32	34	—	—	—

Table 1. Information on FGDs and participants involved.

things analyzed using this tool include time for leisure and traditional dances, planting and harvesting periods, periods of food and income insecurity, timing of hazards like droughts and floods and seasons for illnesses. Thirdly, vulnerability matrices were used to determine hazards, which have the most impacts on livelihoods resources. Livelihoods resources are defined, in this study, as those resources considered most important by smallholder farmers and agro-pastoralists in supporting livelihoods. Participants were asked to prioritize four important livelihoods resources. The matrices also helped to determine the most vulnerable livelihoods resources and to identify adaptation and coping strategies used, and whether the strategies to address the hazards had changed over time. Participants were also asked to decide on the degree of impact of each hazard against the livelihoods resources. The score for a significant impact was 3, for medium was 2, for low was 1 and zero was for no impact. During data analysis, information for each gender group was put together based on similarities and differences between gender groups.

4. Results and discussion

4.1. Trends in hazards causing vulnerability

Tables 2–4 present historical events of the hazards reported by men, women and youth during FGDs. The results show that drought, floods, strong winds, human and livestock pests and diseases, crop pests and diseases were hazards related to climate change that affected community livelihoods. Non-climatic hazards mentioned include low and fluctuation of price for agricultural produce and livestock, robbery of livestock, killings of people with albinism, and tribe wars between the Sukuma and the Taturu. These need to be addressed in order to achieve sustainable livelihoods in the communities. In order to justify these results, FGD participants reported the following:

> *"…Drought…we have lost hope at this point…when it rains, it is so windy…already it has destroyed 15 to 30 houses between January and February this year…the building of the primary society has been destroyed by a strong wind…the cemetery has also been destroyed by floods causing reburying of some bodies…" (Women FGD participants, Mwashata, March 2015).*

Another quotation is:

> *"…El-Niño: It rained about 6 times a day in 1998…there were a lot of crop pests in bulrush millet and cotton. Rats destroyed sweet potatoes. Harvesting of bulrush millet before maturity was necessary to avoid a complete loss…" (Men FGD participants at Kidaru, March 2015).*

Another quotation is:

> *"…In 2002, heavy rains accompanied by 'ice falling' destroyed sweet potatoes and other crops. Fungal diseases, cholera, and malaria became common for humans in that year…" (Women FGD participants at Mwamanimba, March 2015).*

Those quotations inform that farmers especially women had lost hope because of extreme weather events like drought, el Niño rains accompanied by strong winds and ice falling. In addition, killings of people with albinism, which rarely happened in the past, especially in the Sukuma communities of Meatu, were also reported indicating that they were becoming one of vulnerability hazards. Respondents associated killings with national elections because they increased during those periods. The hazards reported by men, women and the youth were almost similar suggesting that all had knowledge about previous and present hazards as shown in the quotations and in **Tables 2–4**. Inspite of the hazards that happened, some years, especially since 2000, were good as justified in the following quotation:

> *"…In 2007, we had all good times, there is nothing we did not do in this year because it was a very good year, we had plenty of food and money, we were drinking and having all the fun…" (Men FGD participants at Kidaru, March 2015).*

It appears that most of the major hazards affecting livelihoods were related to climate change although non-climatic hazards were also concerns. Interestingly, non-climatic hazards were indirectly linked to climate change, which in turn exacerbated poor livelihoods. Tribal wars, for example, were linked to difficulties in making livelihoods aggravated by drought, and therefore causing theft of livestock by the Taturu to the Sukuma communities. This triggered the tribal wars. Similarly, price fluctuation of agricultural produce was attributed to poor productivity resulting from extreme weather events and changes in rainfall patterns. Killings of people with albinism were also attributed to difficulties in making a living in addition to cultural beliefs that albino body parts are sources of wealth. This implies that climate change manifested through, among other things, drought and changes in rainfall patterns, was the major vulnerability hazard having direct and indirect impact to communities' livelihoods.

Tables 2–4 also show frequency of hazards. Drought, that caused famine for example, occurred about 8 times in the previous 15 years since the 2000. A careful look at **Tables 2–4** shows that drought frequencies and famine had increased over time. Natural events, like earthquakes, lightening that kills people, and "ice falling" when it is raining occurred in the previous 15 years. These exacerbated vulnerability of communities' livelihoods. It appears that those natural hazards rarely happened in the 1990s and beyond (**Tables 2–4**). In addition, drought frequencies, strong winds, human and animal diseases and other manifestations of climate change are likely to increase in the future. This leads to the argument that communities' livelihoods are likely to

Year	Events
2015	Drought
2014	Good year with enough rainfalls though accompanied by strong winds in November that damaged houses. Heavy rains occurred in March. There were enough harvests and pastures. Participated in electing local government leaders
2013	Famine, price of cereals went up to TAS 15,000 per cane. Livestock died. People survived by exchanging livestock for cereals. Some survived by a single meal.
2012	Heavy rains and floods
2011	Drought and famine (Kidaru had only three rain days throughout the year)
2010	Drought (At Mwashata village, there were good rainfall and good harvest this year)
2009	Drought and Cholera eruption – Mwamanimba was different, it was a good year, harvests were good and there were about 20 weddings
2008	Enough rains and good harvests, but strong winds damaged houses while pests like rats damaged crops and stored cereals
2007	Good year with enough rains
2006	Famine, rains started in February and livestock died
2005	There was drought and famine (bad year)
2004	This was a local government election year. Cholera eruption. Rains were moderate, but in Mwamanimba there was shortage of pastures for the livestock
2003	Rain stopped before crop maturity
2002	Drought and famine
2001	Enough rains and harvests
2000	Election and census year, killing of people with albinism and there was drought and famine
1999	Famine called *tonja* in Meatu, caused by el-Niño rains that occurred in 1998. Pests destroyed sorghum and millet at an early stage, livestock died. The father of the nation J.K Nyerere also died this year
1998	El-Niño rains. It rained about 6 times a day. A lot of crop pests in millet and cotton. Rats destroyed potatoes. Harvesting before full maturity was necessary to avoid a complete loss
1997	Enough rains
1996	Enough rains and good harvests of bulrush millet especially in Kidaru (*Mwaka Dosa* means a year with bumper harvests), but pests destroyed paddy and millet
1995	Drought and famine. In Mwamanimba, about 30 families migrated to Dodoma, Maswa, Morogoro, Mbeya, Manyoni and Sumbawanga
1994	Famine
1993	Good year because of good harvests (Mwaka Nsumba/Nsoga)
1992	Good year because of good harvests (Mwaka Nsumba/Nsoga)
1991	Was a moderate year (Not so good not so bad)
1990	Good rains, good harvests (good year)
1989	Drought and famine, livestock died and cholera erupted
1988	Drought and livestock died
1987	Good year and harvests
1986	Was a good year
1985	Famine because of war between the Sukuma and the Taturu

Table 2. Trends of events reported by men.

Year	Events
2015	Drought: crop failure, livestock emaciation due to lack of pasture
2014	Good rains, good pastures, but an earthquake occurred and destroyed some houses in Mwashata village
2013	No enough rains, some families migrated to other areas (out of the regions in Tabora). Some men left their families and never came back
2012	Good rains and good harvests
2011	Not so good not so bad year
2010	National election year, a war between the Sukuma and Taturus occurred because the Taturu were stealing livestock in the Sukuma communities. There were strong winds that destroyed houses. There was also poor harvests resulted into famine
2009	Drought and famine. People survived by eating wild food and fruits
2008	Good rains and good harvests, some houses were destroyed by strong winds. Pests also destroyed crops
2007	Good rains and good harvests
2006	Famine. Lightening occurred and they killed some people and livestock
2005	National election year, drought and famine year (*labhalabha*), 20 kg of maize sold 18,000 Tshs (bad year)
2004	Not so good not so bad year in terms of rains and harvests
2003	Famine. Some men left their homes and never come back. About 15 men abandoned their families (wives and children) all together. Some women opted 'sex for money and food' to rescue children
2002	Heavy rain accompanied by ices falling destroyed potatoes and other crops which were still in the farm. Human diseases like small pox, malaria and polio occurred especially to those families which ignored vaccination
2001	Good rains and good harvests
2000	National election and census year, drought and famine, rift valley fever erupted and trachoma
1999	Drought and famine, men moved in search of food and jobs to earn an income, livestock died
1998	Eli-Niño destroyed crops and houses. Eruption of crop pests that destroyed millet, cotton and maize, Rats also damaged potatoes
1997	Eli-Niño came, it caused huge damage on crops
1996	Good rains, good harvests
1995	There was national election
1994	Famine. Some men left their families (wives and children) and never came back. Some of the women who were left by their husbands decided to get married by other men so that they can be assisted to raise their kids
1993	Was a good year (Mwaka Nsumba/Nsoga)
1992	Was a good year (Mwaka Nsumba/Nsoga)
1991	Not so good, not so bad year
1990	There was a human fungal disease which affected adults and children. About five people died. People used traditional medicine until when vaccines were brought in the dispensaries especially in Mwamanimba.
1989	Drought and famine, cholera also erupted
1988	Drought, livestock died
1987	This was a good year because of good rains and good harvests (Mwaka Nsoga)
1986	Was a good year
1985	Famine because of a war between the sukuma and the taturu that occurred in 1984

Table 3. Trends of events reported by women.

Year	Events
2015	Drought: crop failure, livestock emaciation due to lack of pasture
2014	Good rains, good pastures, but an earthquake occurred and destroyed some houses in Mwashata village
2013	No enough rains, some families migrated to other areas (out of the regions in Tabora). Some men left their families and never came back
2012	Good rains and good harvests
2011	Not so good not so bad year
2010	National election year, a war between the Sukuma and Taturus occurred because the Taturu were stealing livestock in the Sukuma communities. There were strong winds that destroyed houses. There was also poor harvests
2009	Drought and famine. People survived by eating wild food and fruits
2008	Good rains and good harvests, some houses were destroyed by strong winds. Pests also destroyed crops
2007	Good rains and good harvests
2006	Famine and lack of pasture. Several lightening occurred and they killed some people and livestock
2005	National election year, drought and famine year (*labhalabha*), 20 kg of maize sold 18,000 Tshs (bad year)
2004	Not so good not so bad year in terms of rains and harvests
2003	Famine. Some men left their homes and never come back. About 15 men abandoned their families (wives and children) all together. Some women opted "sex for money and food" to save children
2002	Heavy rain accompanied by "ice falling" destroyed potatoes and other crops which were still in the farm. Human diseases like small pox, malaria and polio occurred especially to those families which ignored vaccination
2001	Good rains and good harvests
2000	National election and census year, drought and famine, rift valley fever erupted and trachoma
1999	Drought and famine, men moved in search of food and jobs to earn an income, livestock died
1998	Eli-Niño destroyed crops and houses. Eruption of crop pests that destroyed millet, cotton and maize, Rats also damaged potatoes
1997	Eli-Niño came, it caused huge damage on crops
1996	Good rains, good harvests
1995	There was national election and famine
1994	Famine: Some men left their families (wives and children) and never came back. Some of the women who were left by their husbands decided to get married by other men so that they can be assisted to raise their kids
1993	Was a good year (Mwaka Nsumba/Nsoga)
1992	Was a good year (Mwaka Nsumba/Nsoga)
1991	Not so good, not so bad year
1990	There was a human fungal disease which affected adults and children. About five people died. People used traditional medicine until when vaccines were brought in the dispensaries especially in Mwamanimba.
1989	Drought and famine, cholera also erupted
1988	Drought, livestock died
1987	This was a good year because of good rains and good harvests (Mwaka Nsoga)
1986	Was a good year
1985	Famine because of a war between the sukuma and the taturu that occurred in 1984

Table 4. Trends of events reported by the youth.

become more vulnerable in the future especially if smallholder farmers are unable to cope with, or if the coping strategies are not working effectively, and or, if concerted government efforts are not fully integrated in the development programmes to minimize vulnerability.

4.2. Gender vulnerability and seasonality

Table 5 presents seasonal responsibilities by a gender lens. The results show that men, women and youth were involved in agricultural activities. Control and grazing of livestock especially cattle were under men's domination, which is common for most of agro-pastoralist communities with a few exceptions like in Iramba where control was shared between men and women. **Table 5** also shows that women were more responsible for most of agricultural based livelihoods activities relative to their men counterparts, though control over land was under men. This is also common in many agricultural communities in Africa. Seasonal responsibilities differed between men and women. Unlike men, women were busy throughout a year. For instance, in addition to domestic chores, women after farming period engaged in slicing and drying potatoes, collecting and drying wild vegetables and firewood, and participating in weddings. The knowledge of environmental management among women is therefore critical for sustainable management of natural resource base. The opposite may result into environmental degradation that can increase vulnerability to women. For that matter, women have less leisure time compared to men although they played pivotal roles regarding communities' livelihoods. Thus, women were more vulnerable because of increasing time and labor to collect water and firewood, a situation that was aggravated by climate change impacts.

Men spent most of the time for participating in traditional dances and visiting relatives and friends especially between April and September (**Table 5**). This is because, for a good year, harvesting started in April and therefore adequate food was available up to September each year. Thus, communities did not worry about food shortage and food insecurity during that particular period. Therefore, men used that period for leisure, particularly going out of their communities for traditional dances, leaving all responsibilities at home like fetching water and chopping firewood for women and children. Traditional dances that involved men's movements out of the communities happened during both, good and bad years. Youth, especially boys, also spent April to September period, among others, for participating in football league, traditional dances, and for taking livestock to the areas where they could get enough pasture and water (**Table 5**).

Participants reported that communities' vulnerability was high during December, January, February and sometimes March. Vulnerability was highest in January and February because of lack of income, and food insecurity (**Table 5**). In that period, food and income insecurity occur concurrently with dry spells, droughts, high incidence of human diseases like malaria and cholera ([24]; Synneva G et al., [29]) and therefore exacerbating vulnerability. That was also the period for men taking livestock to graze in conserved areas due to lack of grazing areas and water in some villages. In addition, women who were left behind coped by borrowing food or money from friends and relatives to be repaid sometimes later. Truancy among school children increased with vulnerability especially for girls who had to assist their mothers on off-farm activities. It is clear that climate change particularly drought is linked to vulnerability of communities' livelihoods. Those owning livestock, though price of livestock was low

Month	Performed by men	Performed by women	Performed by youth
January	Tilling the land and planting, but no money and enough food	Tilling the land and planting	Tilling the land, weeding, planting and grazing livestock for the men
February	Weeding, but no money and enough food. Normally there is a dry spell of 1 month or more	Weeding. Dry spell	Weeding. Dry spell
March	Harvesting. Floods may occur	Weeding and sometimes harvesting. Floods may occur	Planting and weeding. Floods may occur
April	Harvesting and traditional dances begin. Floods may occur	Harvesting, drying vegetables for future use	Harvesting, Drying vegetables and preparation of building poles
May	Harvesting, traditional dances, digging water holes for cattle's watering points, bricks making and preparing post-harvest storage devices	Harvesting, drying vegetables, slicing potatoes and chopping firewood	Harvesting, football league begin especially for men, slicing of potatoes, preparing bricks, and scaring of bird in the paddy fields. Taking livestock to conserved areas at Mwamanimba
June	Traditional dances (leisure time) and harvesting through traditional self-help groups. Return of livestock from conserved areas at Mwashata	Slicing potatoes, making baskets using local materials, harvesting of agricultural produce	Slicing of potatoes, harvesting and processing through traditional self-help groups and preparation for marriage
July	Traditional dances, building houses, harvesting and transportation of agricultural produce	Slicing potatoes, making and selling local brew especially in Iramba and harvesting of cotton	Slicing of potatoes, making bricks, houses construction, harvesting, football league and doing small scale businesses
August	Traditional dances, visiting relatives and friends, harvesting, processing and storage, brick making and construction of houses	Chopping firewood, visiting relatives and friends, participating in weddings, traditional dances and drinking local brew	Visiting relatives and friends, houses construction, traditional dances, weddings, drinking local brews and football league continues
September	Traditional dances, construction of houses	Chopping firewood and gardening near the river banks	Seasonal movement of livestock, houses construction, and football league
October	Preparing farms, finalizing traditional dances, construction of houses	Copping firewood, farm and seed preparation, and gardening near the river banks	Football league continues, doing small scale businesses, and farm preparation
November	Start of wet season. Farming starts especially tilling the land and planting	Farm and seed preparation, and gardening near the home steads and in the fields afar	Tilling the land with a plow, and planting of maize and cotton
December	Tilling the land and planting. Livestock taken to conserved areas at Mwashata and Kidaru	Tilling the land, planting and gardening near the home steads and in the fields afar	Tilling the land, planting and weeding. Return of livestock from conserved areas at Mwamanimba

Table 5. Seasonal responsibilities.

during food and income insecurity months, could sell to earn income for food to cushion vulnerability. However, dependence on livestock for food and income, in communities like the Sukuma in Meatu where livestock and income are controlled by men, may not help much unless interventions are done to address men's mobility when vulnerability is at the peak. Even though, households without livestock felt the pinch most. The chapter therefore argue that the periods of food and income insecurity were the periods of stress, food insecurity and vulnerability, more so among women and children. June and July were good months because communities had adequate food and income obtained from agriculture and selling agricultural produce respectively especially during good years.

4.3. Gender, hazards and livelihoods resources

Tables 6–8 present livelihoods resources up on, which communities' livelihoods depended and the degree of impact that each of the vulnerability hazards had on each of the livelihoods resources. Livelihoods resources are those resources, considered by the communities, most important in making livelihoods. In this chapter, they include agricultural land; water sources mainly rivers, livestock and institutions like schools and dispensaries. Interestingly, men, women and youth reported similar major vulnerability hazards that affected livelihoods resources (**Tables 6–8**). Reflections in FGDs showed that although non-climatic factors were also concerns, the major vulnerability hazards were climatic factors like drought, floods, strong winds, and human, crop and livestock diseases. These were widespread such that, once happened; there were no safe places in the communities. In other words, the hazards affected everybody although differently depending on gender, ability to cope and households' adaptive capacity.

	Land/farms (natural capital)	**Livestock (natural capital)**	**Water sources, e.g., rivers (natural capital)**	**Institutions, e.g., schools (physical capital)**
Drought	3	3	2	3
Flood	3	2	0	3
Livestock diseases	1	3	0	0
Human diseases	3	1	0	3
Plant insect pests and disease	3	1	0	2

Note: 3 = significant impact on the resource; 2 = medium impact; 1 = low impact and 0 = no impact.

Table 6. Impact scores of vulnerability hazards reported by men.

Hazard	**Land/farms (physical capital)**	**Children (human capital)**	**Water sources, e.g., rivers (natural capital)**	**Institutions, e.g., schools (physical capital)**
Drought	3	3	2	3
Floods	2	2	0	1
Human Diseases	2	3	2	3
Strong Winds	2	2	0	1

Note: 3 = significant impact on the resource; 2 = medium impact; 1 = low impact and 0 = no impact.

Table 7. Impact scores of vulnerability hazard reported by women.

Hazard	Land (natural capital)	Water sources, e.g., rivers (natural capital)	Livestock (natural capital)	Institutions, e.g., schools (physical capital)
Drought	3	3	3	3
Strong winds	0	0	2	3
Human diseases like cholera and malaria	0	0	0	3
Crops pesticides	1	2	3	3

Note: 3 = significant impact on the resource; 2 = medium impact; 1 = low impact and 0 = no impact.

Table 8. Impact scores of vulnerability hazards reported by youth.

Synthesis with FGD participants showed that drought occurred at any point in time during wet seasons while floods occurred normally during March and April, but could also occur at any point in time during wet seasons. The wet season started in October/November and ended in April/May [24]. Prevalence of cholera and malaria was high in wet seasons. In most cases, occurrence of the climatic hazards was difficult to predict. Each of the hazards negatively affected livelihoods resources. The impact manifested through crop failure and lack of pasture that definitely caused food insecurity and famine. The aggregate impacts of the climatic hazards affected women most than men because control over livelihoods resources, that are critical for coping and adaptation to climate change impacts like livestock and land, is under men domination [1]. In addition, men's mobility reduced their vulnerability relative to women counterparts implying that women were more vulnerable to the impact. This implies that although mobility helped men to survive against climatic impacts it aggravated vulnerability among women and children.

A synthesis in FGDs showed that drought affected land through soil degradation, which, like soil erosion, contributed to loss of soil fertility that eventually resulted into crop failure and poor crop production. It also contributed to lack of pasture, and drying up of water bodies like rivers. That means drought affected natural capital in the communities. The ultimate impact of the hazards was famine that, among others, negatively affected school attendance among pupils. In that way, famine affected human capital among women and children. Human diseases like cholera and malaria, affected human capital and labor force in agriculture and livestock, while livestock diseases affected animal power and agricultural production. Generally, human, crop and livestock diseases had effect on financial capital through reduced production and productivity and increasing cost in controlling them.

Strong winds destroyed human shelters and public buildings like classrooms and therefore had effect on physical and human capital as well. Focus groups commented that when classrooms were damaged by a strong wind, pupils' attendance among boys and girls was affected as well as the learning process. Girls were likely to be more affected because of their subordinate position in agricultural and agro-pastoralist communities. Girls' subordination is common in most rural areas in Africa [1]. We therefore argue that the poor learning process caused by lack of classrooms as a result of climatic hazards had negative impact on aggregate human capital, which is critical for improving communities' livelihoods. If this trend continues, vulnerability to climate change impacts is likely to aggravate in the future. Some development partners especially World Vision Tanzania (WVT) had intervened through "food provision" to the pupils at school. Yet, this may not be enough because the intervention is likely to be not sustainable. Therefore, other policy interventions, that can ensure sustainable food security, have to be in place to overcome the situation.

Men and women reported serious impact of drought on land, livestock and school institutions. Similar climatic hazard was report to have medium impact on water resource. Floods had serious impact on land and school institutions. Diseases had serious impact on land, livestock and school institutions (**Table 6**). Women reported serious impact of human diseases on children and school institutions (**Table 7**). In addition, youth reported serious impact of drought on land, livestock, water resource and school institutions. They also reported serious impact of strong winds and human diseases on school institutions, and crop insect pests and diseases on livestock and school institutions (**Table 8**). This shows interaction between the climate change and livelihoods.

4.4. Gender adaptation and coping strategies against hazards

Discussions in focus groups showed that men and women had adopted various strategies to cope with hazards like droughts and their outcomes including famine, lack of pasture, crop and diseases and pests. For instance, the whole family could permanently migrate to other regions in the country, where it was perceived to be receiving adequate amount of rainfall, or where there was no drought, and that the region is suitable for agriculture - in terms of land availability and fertility - and livestock keeping. Those areas include some parts of Tabora, Mbeya, Morogoro, Geita and Rukwa, to name a few. To justify migration men's FGD participants at Mwamanimba reported the following:

> *"…in 1995, about 30 families out-migrated to Tabora, Morogoro, Mbeya and Sumbawanga, and from that time to date almost half of the households in the village has permanently migrated…" (Men FGD participants at Mwamanimba, March 2015)*

Based on that quotation, the 1995 was a dry year accompanied by famine that caused permanent family migration especially at Mwamanimba in Meatu. Since then, more families had permanently migrated responding to an increased frequency of drought in the 2000s. Surprisingly, other families migrated into the same village suggesting that vulnerability due to climate change is complex and widespread. In addition, climatic hazards that induced families' out-migration were inter-linked between climate change and non-climatic change like changes in land use, land cover and vegetations. For instance, the grazing land had been converted into agricultural land because of population increase and the quest to increase production that dwindled because of drought and changes in rainfall patterns. This implies that families migrated in search of agricultural and grazing land, in addition to water for domestic use.

In agro-pastoralist communities like in Meatu and Iramba, wealth is stored in livestock [29], which can be exchanged for food or income to buy food and other necessities so as to sustain the families. Therefore, families did all the needful to ensure that livestock did not perish because of lack of pasture and water. On one hand, migration was a coping strategy, but on the other hand, it was an adaptation strategy for families that had practiced it for many decades. When the entire family moved, mobility increased household vulnerability for food insecurity and famine because families lost time for a long distance migration instead of dealing with livelihoods activities like farming. Migration also disturbed livelihoods natural resource base thus increased communities' vulnerability, more so among women, elderly and children who are more vulnerable. Sometimes, men alone moved out seasonally with or without livestock. This was justified by one FGD participant at Mwashata as follows:

> *"…in 2006, I moved through different districts to sustain my cattle because of lack of pasture… the districts were Bariadi, Maswa, Kwimba, Geita, Misungwi, and Shinyanga rural…during these movements four cattle died due to long distance, lack of water and pasture and the fact that they were old…" (Men FGDs participant aged 61 at Mwashata, Meatu, March 2015)*

Based on that quotation, it can be deduced that the 2006 was a famine year with inadequate pasture and food insecurity. When men moved without livestock, the main agenda was to sell labor in different villages and towns. This had been practiced for many years and so qualifying to become an adaptation strategy if it were anticipated and planned. Going for artisanal mining in mining areas in the country like Geita, Kahama and Mwadui, especially among men and youth was also reported. Men's movements to sell labor for food and income was supported by an improvement in rural roads infrastructure in the 2000s implying less vulnerability among communities relative to the period before the 2000s. However, vulnerability among women, children and the elderly who remained at home did not decrease concomitantly. It is the women who had to feed, in addition to domestic chores, the family members remained behind through skipping some meals, reducing amount or the number of meals from say three to one, and depending on wild food and fruits. Women FGD participants at Kidaru justified by reporting that:

> *"…in 2009, we survived by eating wild fruits called 'Mahama'…we collected these wild fruits in the mid night, so we used to go in the bush during the night because if you wait until morning you may be competing with baboons because they also eat them…" (Women FGDs participants, Kidaru, March 2015).*

That quotation implies that climate change had affected not only humans, but also wild animals such that wild animals and humans, especially women who had limited control over livelihoods resources and limited mobility shared similar wild food. In addition, FGDs reported that women survived by being re-marrying to another men or opting "sex for money" to buy food or "sex for food" when their husbands were away. Being forced by the circumstance to re-marry or succumbing to "sex for money" or "sex for food" increased number of sexual partners among women. This suggests increased chances of succumbing to sexual transmitted infections (STIs) including HIV/AIDS. It also implies that sexual practicing among women, when husbands were away, was a coping strategy. It appears that one of the major adaptation strategies for men was movement with or without livestock. Some did not get back or remit money back home. While taking livestock to conserved areas during pasture crisis was a coping or an adaptation strategy to climate change impact, it was a vulnerability factor among women and children, and also created pressure on biodiversity because of concentration of livestock in the conserved areas.

Reflections in FGDs showed that communities received food aid from the local governments and non-governmental organizations particularly World Vision Tanzania during food insecurity months. Food relief seemed to increase in the previous 15 years, in which was provided almost each year. This is translated to increased climatic hazards like droughts that affected crop productivity. Some women relied on doing small scale businesses, food and money borrowing from relatives and friends in coping with droughts, food insecurity and famine. Borrowing had increased in the previous 20 years. This is not new, but borrowers returned without interest in the past, suggesting strong social capital and a culture of self-help in the communities in the past. However, FGDs commented that an interest had been introduced since the 1990s following increasing incidence of food borrowing largely due to re-occurrences of crop failure and famine. This implies that climatic hazards had weakened social networks and trust in the communities and that it had increased vulnerability among borrowers, in most cases, women who borrowed when men were away. Reflections in FGDs showed that, while men could get some money and food for selling labor when they were away from their families, it was a challenge for women, who left at home, to support family members through small scale businesses without proper skills and also through "sex for money and food." The strategies adopted by women were not reliable and sustainable given that they prevailed during hardship periods in terms of food insecurity, famine and lack of income, in which everybody in the community including men, who contracted "sex for food" and or "sex for money" with women, was a victim.

5. Conclusions and policy recommendations

Climatic hazards have complex and overlapping outcomes in semi-arid environment in Tanzania. They have negative impact on natural, social, financial, physical and human capitals that are critical for community livelihoods. The trends of the hazards had increased over time, in the previous 30 years, concurrently with famine and disturbances on communities' livelihoods. Communities, men and women, had differently adopted coping and adaptation measures in dealing with vulnerability. Men's strategies took place outside the home while women's strategies were mainly conducted at home. The major coping and adaptation strategies for men were related to mobility. Interestingly, women's adaptation and coping strategies were not reliable and sustainable such that they were not effectively working resulting into more vulnerability among women relative to men counterparts. These results have policy implications calling concerted efforts from development actors to address the situation. To that effect, the chapter recommends the following:

- Development programmes implemented by different stakeholders like the central and local governments should make sure that women are given skills and involved in environmental management interventions like tree planting, water projects and soil moisture and fertility conservation because they are main users and agents of environmental management. This can rehabilitate the degraded land to improve food security.

It can also restore availability of firewood to women's proximity that in turn reduces gender vulnerability.

- Strategies to deal with diseases like malaria and cholera as well as crop and livestock insect pests and diseases should be integrated in the development planning at local government level because it was difficult to predict the hazards like floods and droughts that occurred concomitantly with the diseases. Children, women and elderly should be given special attention because they have special health needs.
- Local governments should put in place sustainable nutrition programmes to address food insecurity and famine among women and children especially during food and income insecurity periods. Women should also be given skills and credit support to start and manage tangible small scale businesses. They should also be imparted knowledge regarding HIV/AIDS and other STIs that seemed to increase vulnerability among them.
- Suggested by FGD participants, the central government can intervene through supporting irrigated farming, tree planting, construction of water reservoirs, support in terms of drugs and experts in village dispensaries, drugs and extension officers for crops and livestock, and price control mechanism especially for cotton, which seemed to be unstable influenced by private buyers. In addressing vulnerability, the strategies should be gender sensitive because vulnerability is differentiated by gender lines. Those strategies are critical in improving and making community livelihoods sustainable with potential to addressing vulnerability to climate change as well as vulnerability to non-climatic hazards, which are mainly driven by poor communities' livelihoods. In this case, any strategy to address any kind of vulnerability should put community livelihoods at the center and so "livelihood centered approach' in addition to restoration of natural resource base.

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Section 4

Water Resources and Policies

Chapter 4

Long-Term Effects of Effluent Water Irrigation on Soil Chemical Properties of Sand-Based Putting Greens

Hanan Isweiri and Yaling Qian

Additional information is available at the end of the chapter

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Abstract

The increase of the world's population and the decrease of freshwater resources have led to increased use of alternate water resources to meet the water need. Using treated wastewater (effluent water) for urban landscape irrigation has become a common practice to alleviate freshwater shortage. Golf courses are the leading urban landscape users of effluent water, because intensively managed turf can use nutrients in the wastewater efficiently. The objectives of this study were to assess changes in soil chemical properties of sand-based putting greens, following conversion from freshwater irrigation to effluent water irrigation, and identify potential concerns related to long-term use of effluent water on sand-based greens. Soil samples were collected and analyzed from greens at the Heritage Golf Course in Westminster, Colorado. The course started to use effluent water for irrigation in 2000. Nine out of eighteen (1, 3, 5, 7, 9, 11, 13, 15, 17) greens were selected for soil sample collection. Soil samples (0–10 cm below soil surface) were collected in September of 1999, 2003, and 2009. Soil test data showed that the soil's chemical characteristics changed over time. Soil organic matter (SOM) increased from 0.12 to 1.5%, and cation exchange capacity (CEC) is increased by as much as double over nine years. Extracted phosphates increased by 388% after nine years of effluent water use. Exchangeable calcium, magnesium, potassium, and sodium also increased, by 198, 116, 148, and 452%, respectively, over nine years of effluent water irrigation. In addition, increases over time were found for extractable iron, manganese, copper, zinc, and aluminum. In conclusion, using effluent water for irrigation has both benefits and risks. Increased salinity (EC) and sodium levels are the greatest risks when using effluent water; however, to a certain degree, these can be managed through appropriate cultural practices such as leaching and adding gypsum. Supplemental nutrients and decreased fertilizer costs are the greatest benefits of using effluent water for irrigation. Our results showed that released nitrogen, phosphorus, potassium, and magnesium levels increased in the soil after using effluent water, which would be beneficial for the grass and lowering the fertilizer's cost.

Keywords: treated wastewater, effluent water, irrigation, soil salinity

1. Introduction

The increase of the world's population and the decrease of freshwater resources have led to increased use of alternate water resources. In contrast, as the population increases, wastewater production increases. In many arid and semiarid areas in USA, Australia, and Israel, using freshwater for turfgrass and landscape irrigation has become rare. Consequently, using treated wastewater (effluent water) for irrigation has become a common practice to alleviate freshwater shortage. In addition to the growing concerns of the future water supply, the more stringent wastewater discharge standards make use of effluent water increasingly attractive.

Golf courses are the leading urban landscape users of effluent water. A survey conducted by the National Golf Foundation (NGF) reported that approximately 13% of golf courses in the US use effluent water for irrigation, with 34% of golf courses in the Southwest US doing so [1]. In Colorado, approximately 25% of golf courses are using effluent water for irrigation.

Effluent water is any water after residential and sometimes industrial use that undergoes significant treatment at a sewage treatment plant, to meet standards set by federal or state water laws and regulations. This water is usually suitable for various reuse purposes including irrigation. During treatments, suspended solids are removed, pathogens are disinfected, and partial to substantial reduction in nutrient concentrations occurs, depending on treatment stage [2, 3]. Currently, effluent water used for turf and landscape irrigation must be disinfected [4].

However, using effluent water has some disadvantages. Public health is the first concern due to the pathogens it may contain, but that is less of a concern if used for nonedible plants. Effluent water may contain different levels of dissolved solids, ions, nutrients (NO_3 and P_2O_4), and other elements. Increases in soil salinity and sodium are potential problems associated with using effluent water irrigation. Salinity has harmful effects on nonhalophyte plant growth and development as well as making soil water less available for the plants. Increased sodium level (sodicity) in the soil leads to disaggregation of soil to its components and damages the soil structure. In addition, researchers suggest that using effluent water for irrigation may affect soil chemistry over time [5–9]. Accordingly, the use of effluent water for irrigation requires monitoring and the use of management practices to minimize any potential adverse effects on soil and plants.

On the other hand, using effluent water for irrigation has some advantages. Effluent water contains some nutrients that can be used by plants. Nitrogen (N) and phosphorus (P) as well as some small amounts of micronutrients are found in effluent water. Studies have showed that plant yields increased by using effluent water when compared to freshwater irrigation [10]. This increase is due to the nutrient concentrations such as N and P in effluent water and their effect on plant growth [10]. High-quality effluent water has become available for golf course irrigation, and it decreases the fertilizer cost because of nutrient availability in the water [4]. Also, using effluent water is less expensive when compared to other alternative irrigation resources such as desalinized seawater [11].

Many studies have been published regarding the effect of using effluent water on soils in urban landscapes. However, no research is available regarding the impacts of effluent water irrigation on sand-based root zones on golf course putting greens and sports fields. Research is needed to determine the effect of using effluent water on sand-based root zones on putting greens. Most golf course putting greens are constructed based on the United States Golf Association (USGA) putting green construction recommendations. USGA putting green consists of 30 cm sand-based root zone that contains 90% sand and 10% organic matter by volume. The sand-based root zone overlays a 10-cm-deep gravel blanket to provide the best soil conditions for turfgrass growth and to minimize compaction and optimize drainage. Sand-based putting greens allow for good aeration and drainage, and that is important to maintain a good playing surface. Sand is suitable for the putting green's function because it is resistant to soil compaction and has good filtration and percolation rates. However, it has low organic matter, which may affect its ability to hold nutrients [12]. Organic matter, typically peat, is often added to improve water and nutrient-holding capacity [13]. With putting green's special nature, using effluent water for irrigation needs to be investigated over the long term to address the impact of effluent water on putting green soil properties.

The objectives of this study were to:

1. Assess changes in soil chemical properties of sand-based greens following conversion from freshwater irrigation to effluent water irrigation.
2. Identify potential concerns related to long-term use of effluent water on sand-based greens.

2. Materials and methods

2.1. Study location

The study was conducted at Heritage Golf Course in Westminster, Colorado, which is located north of metro Denver (39° 53′ 59.34″ N 105° 07′ 00.04″). The course started to use effluent water for irrigation in 2000. Nine out of 18 (1, 3, 5, 7, 9, 11, 13, 15, 17) greens were selected for soil sample collection. Soil samples (0–10 cm below soil surface) were collected in September of 1999, 2003, and 2009.

Soil samples were analyzed for soil pH, extractable salt content (Ca, Mg, K, Na, Fe, Mn, Cu, Zn, P, and B), base saturation percent of Ca, Mg, K, and Na, soil organic matter (SOM), and cation exchange capacity (CEC) by Brookside Laboratories, Inc. (New Knoxville, OH). Soil pH was analyzed using 1:1 H_2O procedure; 1:1 is the most common ratio used for soil-water pH. It is performed by mixing an equal volume of soil and deionized water. Soil samples were extracted using the Mehlich III extract (0.015 M NH_4F + 0.20 M CH_3COOH + 0.25 M NH_4NO_3 + 0.013 M HNO_3 + 0.0005 M EDTA chelating agent) to determine Ca, Mg, K, Na, Fe, Mn, Cu, Zn, B, and P by inductively coupled plasma-emission spectrophotometry instrumentation. Mehlich III is a procedure widely used for extraction of plant available macro- and micro-nutrients in soils that have an acidic or neutral pH, by using a dilute acid-fluoride-EDTA solution with pH 2.5 extracted [14]. Mehlich III extracted Ca, Mg, K, and Na plus soil buffer pH data are used to calculate CEC. Base saturation percent of Ca, Mg, K, and Na was calculated by dividing the extracted Ca, Mg, K, and Na by the calculated CEC, respectively. Base saturation percent of Na is considered the exchangeable sodium percentage (ESP). Soil organic matter was determined by reaction with $Cr_2O_7^{2-}$ and sulfuric acid. The remaining unreacted $Cr_2O_7^{2-}$ is titrated with $FeSO_4$ using ortho-phenanthroline as an indicator, and oxidizable organic matter was calculated by the difference in $Cr_2O_7^{2-}$ before and after the reaction [15]. Estimated N release is calculated to determine the potential amount of N released annually by SOM decomposition.

2.2. Data analysis

Data were analyzed by analysis of variance (ANOVA) [16] to test the effect of irrigation with effluent water on individual soil chemical properties. Comparisons between years were examined, and means were separated by LSD at 0.95 level of confidence. Regression analysis was used to examine the changes in individual soil parameters over time after the use of effluent water for irrigation.

3. Results and discussion

Effluent water analysis showed that sulfate (182 mg L^{-1}), bicarbonate (125 mg L^{-1}), chloride (120 mg L^{-1}) and sodium (101 mg L^{-1}) are the most dominant elements in the water (**Table 1**).

On average, soil pH was 6.9 at the initiation of the study (**Figure 1**). ANOVA test showed no changes in pH for 9 years after using effluent water (**Figure 1**). These results are similar to the findings in a previous study on the fairways of the same golf course [9]. These results likely were due to the use of sulfur (S) burner units on the golf course irrigation system. After transitioning to effluent water, the Heritage Golf Course installed a sulfur burner. Sulfur burner units heat elemental S to create sulfurous acid for injection into irrigation water to reduce the bicarbonate content and pH [7]. The fact that we did not see an increase in soil pH suggests that the S burner was effective in controlling soil pH associated with effluent water irrigation. Soil pH increases have been observed by others in soils under effluent water irrigation [7, 17]. At this site, soil pH was maintained without change over 9 years by reducing the bicarbonate level in the irrigation water and releasing H^+ into water and soil.

The SOM was significantly different among the sampling years with the means linearly increasing from 1999 to 2009 (**Figure 2**). Comparing before using effluent water (1999) and after 9 years of using effluent water (2009) at the Heritage Golf course, we found that SOM significantly increased ($R^2 = 0.83$). At the initiation of the study in 1999, SOM content was 0.12%, which increased to 1.5% in 2009. The average increase was 0.15% annually. To calculate the total carbon (C) sequestration from SOM, an assumption was made that SOM contains 58% C, and putting greens have 1.6 g cm^{-3} bulk density. The average annual total C sequestration was 1.4 t h^{-1} yr^{-1} during 9 years of using effluent water. Our calculation for this site was higher than the estimation that was reported by Qian and Follett [18] that soil C sequestration rate was 1.1 t h^{-1} yr^{-1} on golf course putting greens. Soil organic matter is a significant component in turfgrass systems; it affects soil porosity, water and nutrients retention, and percolation in the sand-based root zone. In addition, the calculation of C sequestration from SOM could be helpful to understand the role of turfgrass systems in storing C in the soil.

Water quality parameters	
pH	7.4
NH_4–N	0.8 mg L^{-1}
NO_3–N	2.9 mg L^{-1}
Total P	0.6 mg L^{-1}
Total dissolved salts	638
Conductivity	0.99 dS m^{-1}
Sodium absorption ratio (SAR)	3.05
Adjusted SAR	5.74
Na	101 mg L^{-1}
Cl	120 mg L^{-1}
Bicarbonate	125 mg L^{-1}
Ca	67 mg L^{-1}
Mg	11.8 mg L^{-1}
Sulfate	182 mg L^{-1}
B	0.21 mg L^{-1}
Fe	0.31 mg L^{-1}
K	16.9 mg L^{-1}
Total suspended solid (TSS)	9.1 mg L^{-1}

Table 1. Effluent water quality used in Heritage Golf Course (season average).

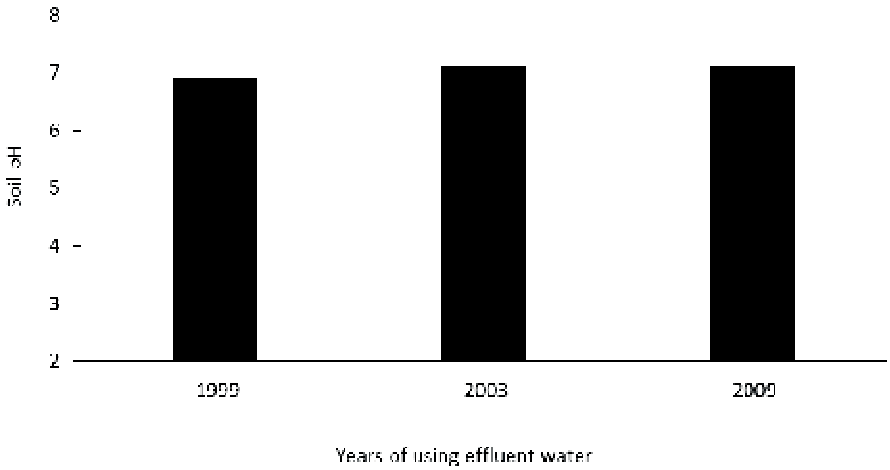

Figure 1. Effect of using effluent water irrigation on soil pH. Different letters indicate significant differences using LSD (*P* < 0.05).

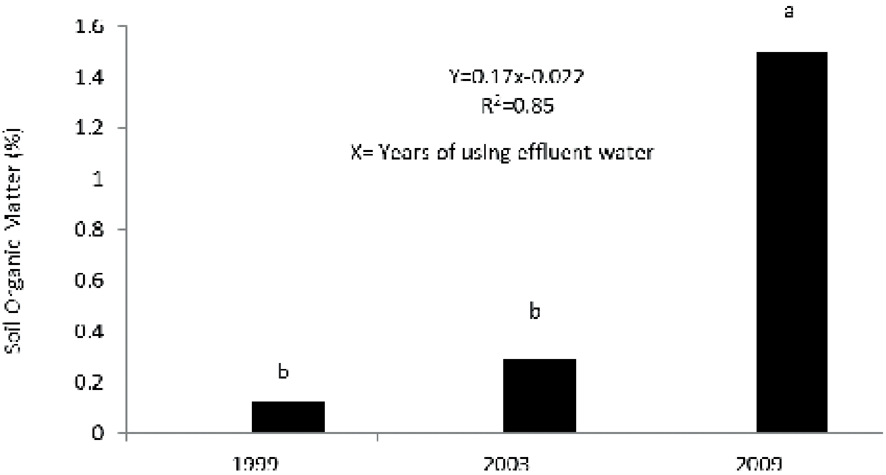

Figure 2. Effect of using effluent water irrigation on soil organic matter. Different letters indicate significant differences using LSD ($P < 0.05$).

Putting greens had low CEC (1.9 $\text{cmol}_c\ \text{kg}^{-1}$) at the beginning of the experiment. This was because it was mostly sand with low SOM and contained low inorganic colloids. Soil CEC is increased by 174% over the course of the experiment ($R^2 = 0.86$) and by an average rate of 0.38 $\text{cmol}_c\ \text{kg}^{-1}$ (**Figure 3**). Organic matter has very high CEC. The significant increase in soil CEC observed in this study is likely due to the increase in SOM.

The estimated N release showed a highly significant increase over time ($R^2 = 0.90$), and the percentage increase was 1117%, with an annual rate of 5.6 kg $\text{ha}^{-1}\ \text{yr}^{-1}$ compared to the year

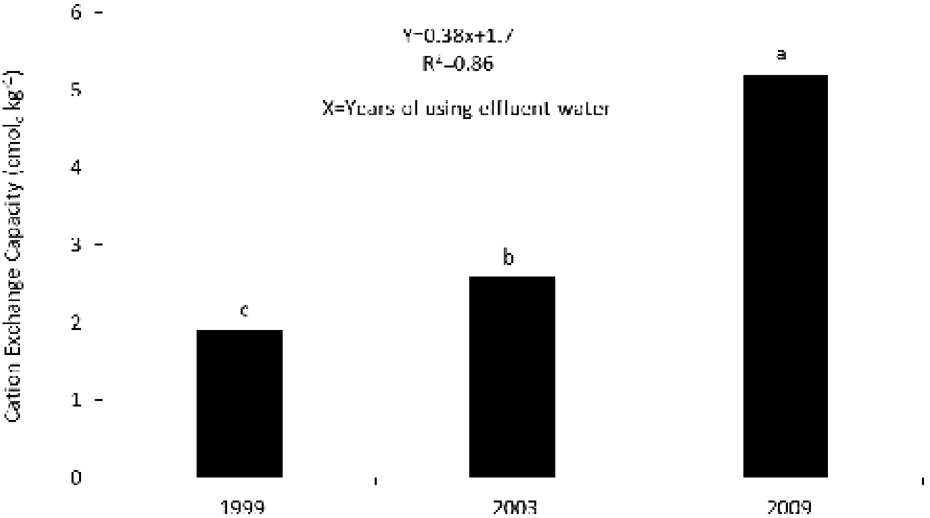

Figure 3. Effect of using effluent water irrigation on cation exchange capacity. Different letters indicate significant differences using LSD ($P < 0.05$).

before using effluent water which was 4.6 kg ha^{-1} (**Figure 4**). Estimated N release is an estimate of N potentially released annually by decomposition of SOM. Estimated N release could be affected by many factors such as soil moisture, temperature, and soil type. This large increase was due to the fertilization and organic matter increase as well as substances added by effluent water because it often contains significant concentrations of organic nutrients, such as N and P [19]. Increases in this category were also a result of increased biomass production that translated to increases in SOM and eventually available N from organic matter decomposition.

Soluble S increased over time ($R^2 = 0.82$; **Figure 5**). The percentage increase during the 9 years of using effluent water was 413%. As mentioned earlier, this increase of S content over time was a result of using S burner to inject elemental S into irrigation water to reduce pH and bicarbonate concentration in effluent water [7]. Turf managers at Heritage Golf Course encountered a problem of increased black layer beneath putting green surfaces since 2003. Black layer is the formation of a layer of metal sulfide [20, 21], which forms when hydrogen sulfide (H_2S) gas reacts with metal elements in the soil. Hydrogen sulfide gas is produced by sulfur-reducing bacteria (SRB). Black layer is typically associated with turfgrass chlorosis, wilting, thinning, and sometimes death.

Soluble S is the substrate for S reduction activity that leads to black layer. Therefore, the use of a S burner under effluent water irrigation might have partially contributed to the increased occurrence of black layer. Further research is needed to address the potential relationship between the incidence of black layer and effluent water irrigation.

In addition, extracted phosphates increased over time ($R^2 = 0.83$; **Figure 6**), and the percentage of increase during 9 years of using effluent water was 388%. This increase was expected because effluent water usually has more soil phosphates than freshwater. Increases in phosphates over years of using effluent water irrigation have been recorded in previous studies [9, 22].

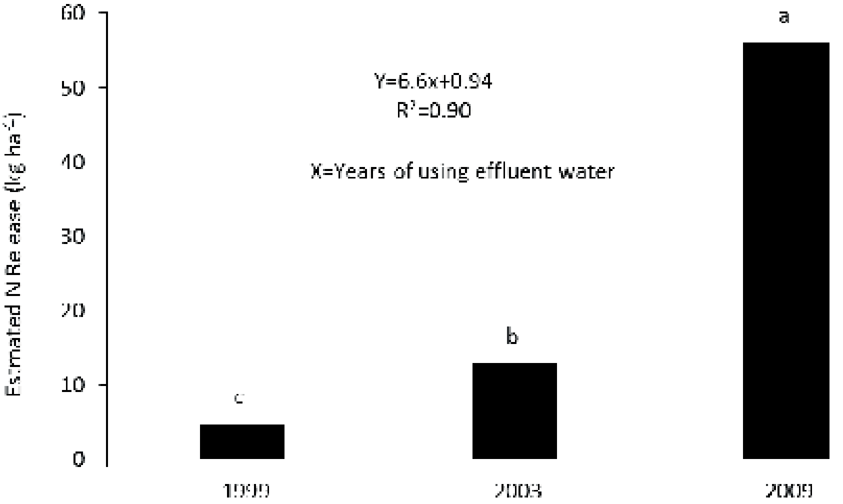

Figure 4. Effect of using effluent irrigation on soil's estimated N release. Different letters indicate significant differences using LSD ($P < 0.05$).

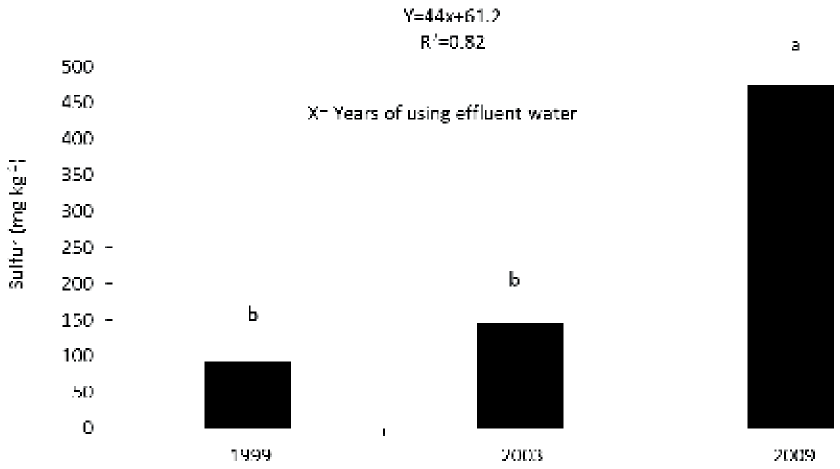

Figure 5. Effect of using effluent irrigation on soil soluble sulfur content. Different letters indicate significant differences using LSD ($P < 0.05$).

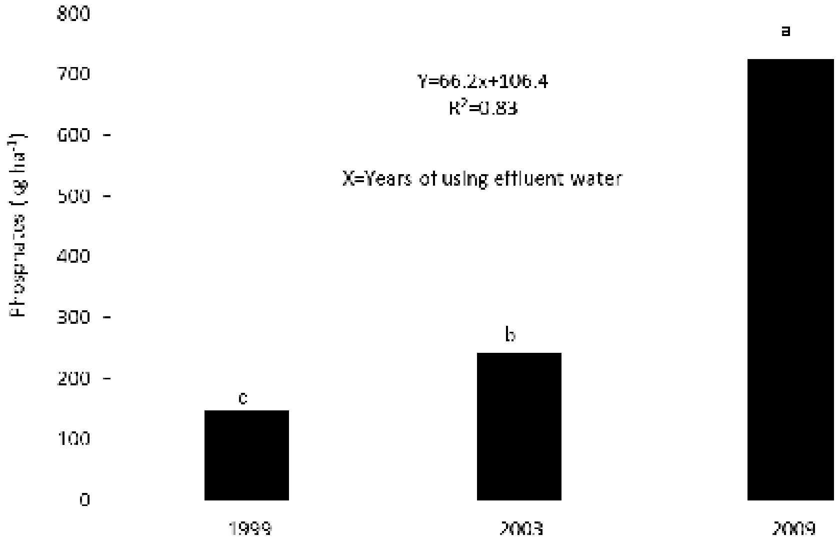

Figure 6. Effect of using effluent irrigation on soil phosphates. Different letters indicate significant differences using LSD ($P < 0.05$).

Similarly, exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) significantly accumulated over time after using effluent water (**Figures 7–10**). The percentage of the increase after nine years of using effluent water was (Ca) 198%, (Mg) 116%, (K) 148%, and (Na) 452%. Exchangeable Na increased to 156 kg ha^{-1} after nine years of using effluent water. This increase could be due to the use of effluent water irrigation as some research has indicated. Soil Na concentration increased almost 5.5 times since the start of using effluent water, and the value (156 kg ha^{-1}) was in the moderate risk range (>210 is in high risk) [23]. A study done in 2005 found that effluent water provided enough K, Ca, and Mg for plants [24]. The authors suggested that soil with excessive amounts of K could lead to base saturation imbalance, and highly soluble salts tie up other elements such as B, Ca, and Mg. In contrast, higher amounts of Mg appeared to be a problem in clay soil, but it could help stabilize sandy soil. In this study, however, no clear pattern was found over time for potassium base saturation percentage (**Figure 11**).

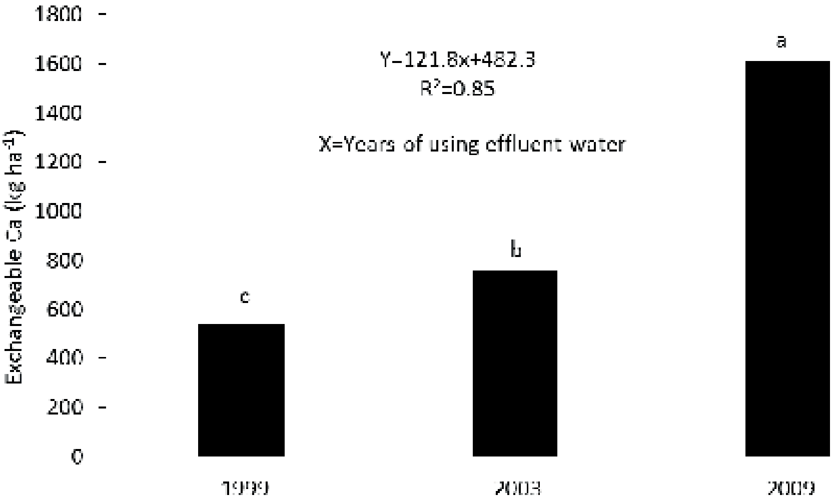

Figure 7. Effect of using effluent irrigation on soil exchangeable calcium. Different letters indicate significant differences using LSD ($P < 0.05$).

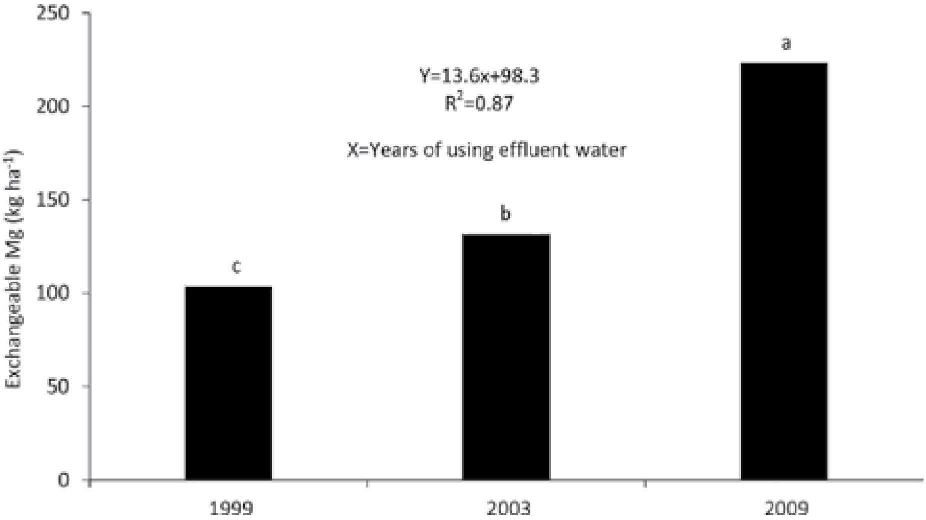

Figure 8. Effect of using effluent irrigation on soil exchangeable magnesium. Different letters indicate significant differences using LSD ($P < 0.05$).

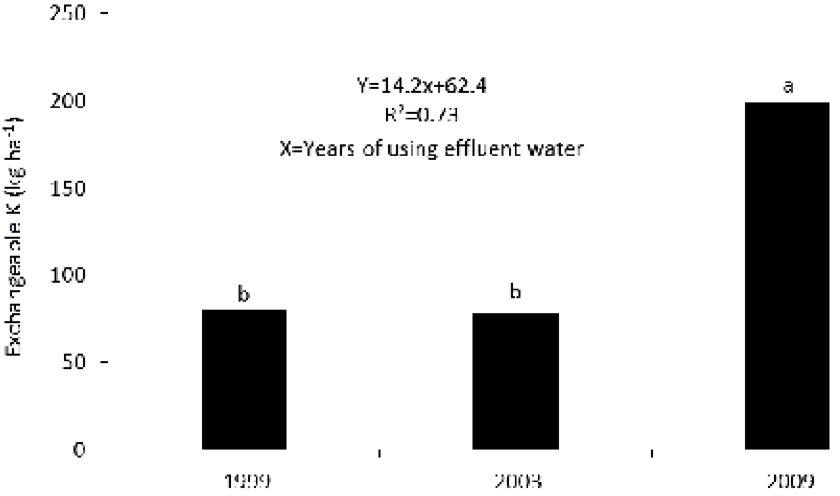

Figure 9. Effect of using effluent irrigation on soil exchangeable potassium. Different letters indicate significant differences using LSD ($P < 0.05$).

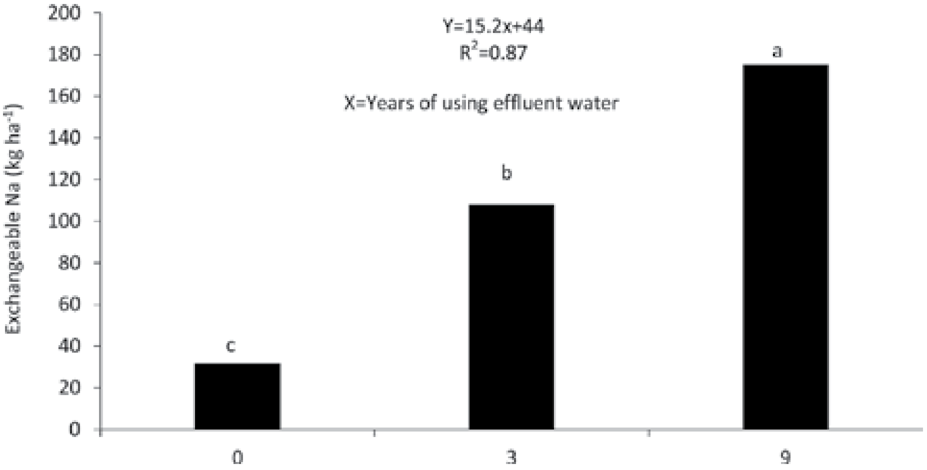

Figure 10. Effect of using effluent irrigation on soil exchangeable sodium. Different letters indicate significant differences using LSD ($P < 0.05$).

Increase in Na base saturation percentage was observed after nine years of effluent water irrigation at an average rate of 0.27% per year (**Figure 11**). Elevating exchangeable sodium percentage (ESP) observed over several years of effluent water irrigation can be of concern with regard to the preservation of water permeability and hydraulic conductivity on putting greens. ESP is a measurement of sodium hazard in soil, and ESP more than 15% can cause sodicity problems. Soil hydraulic conductivity decreases as ESP increases. However, sodicity depends on soil type. Soil with high clay content is affected more by ESP. Effluent water can cause Na build up over time in the soil. High concentrations of Na can affect the ability of water to move through the soil, that is, decrease infiltration.

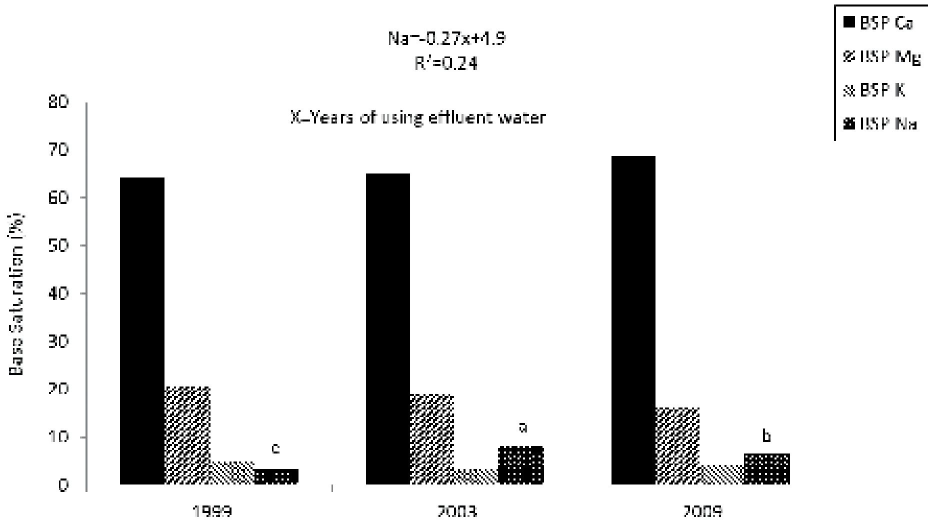

Figure 11. Effect of using effluent irrigation on soil base saturation Ca, Mg, K, and Na. Different letters indicate significant differences within the parameter using LSD ($P < 0.05$).

In this study, a slight increase was recorded in the Ca base saturation percentage ($R^2 = 0.35$). In contrast, a reduction in Mg base saturation percentage was recorded ($R^2 = 0.66$) (**Figure 10**). Calcium and Mg affect each other's availability in the soil, and high Ca may tie up magnesium. However, the Ca/Mg ratios matched the balanced ratio at every sampling time (2.1–5.9) [25]. In general, the base saturation percentages for Ca, Mg, and K in this putting green are considered to be in the ideal or balanced ranges that many soil laboratories use to interpret soil test results. According to the basic cation saturation ratio theory, ideal plant growth will be achieved only when the soil's exchangeable Ca, Mg, and K concentrations are in range of 60–70% Ca, 10–20% Mg, and 4–6% K [26].

A significant increase over time was observed for extractable Fe ($R^2 = 0.81$). The percentage increase was 354% after 9 years of using effluent water, with an average rate of 25 mg kg^{-1} per year (**Figure 12**). These results were in agreement with a short-term (45 days) study done in Iran in 2011 [27]. The authors found that irrigation with wastewater significantly increased extractable Fe by 13% compared to the site that was irrigated with freshwater [27]. Although the effluent water for this course had low levels of Fe (0.3 mg L^{-1}), the soil extractable Fe concentration significantly increased after using effluent water. After nine years of using effluent water, extractable Fe was 288 mg kg^{-1}. Soil pH plays an essential role in micronutrient availability to plants. The availability of micronutrients such as Fe, Mn, and Zn in soil solution begins to decrease when soil pH is above 6.5. As soil pH increases, the availability of Fe decreases. As result, Fe deficiency is common in high pH soil. Iron is essential for chlorophyll synthesis and photosynthesis [28]. Effluent water could supply the soil with Fe with a proper soil pH range. In this site, Fe concentrations after nine years of using effluent water were in the ideal range (100–300 mg kg^{-1}).

Likewise, extractable copper (Cu), manganese (Mn), and zinc (Zn) increased significantly over time ($R^2 = 0.86$, 0.87, and 0.89, respectively). The increased percentages after using effluent water were 290, 1220, and 1608%, by an average rate around 1.0, 3.2, and 2.1 mg kg^{-1} yr^{-1}, respectively,

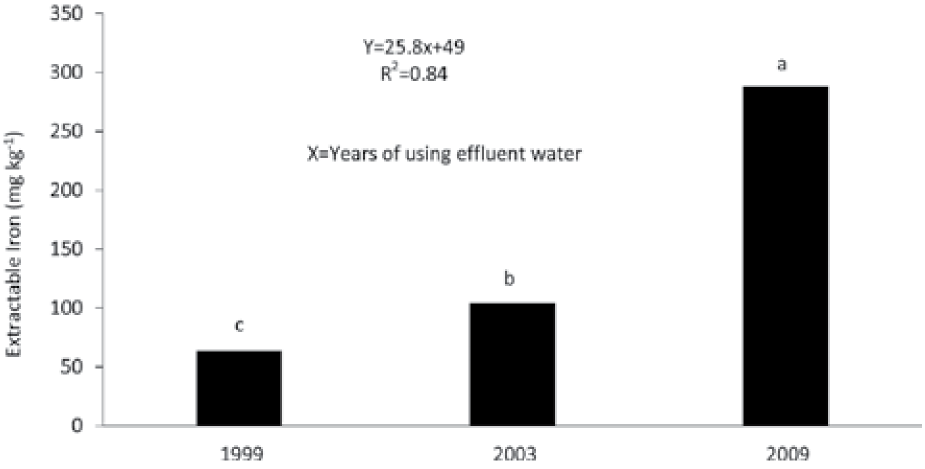

Figure 12. Effect of using effluent irrigation on soil extractable iron. Different letters indicate significant differences using LSD ($P < 0.05$).

for Cu, Mn, and Zn, respectively (**Figure 13**). This finding is in disagreement with the previous study for fairways on the same golf course which suggested that no pattern of change was recorded for extractable Cu, Mn, and Zn after using 9 years of effluent water [9]. These micronutrient availabilities are similar to the availability of Fe and depend on pH as well. Sandy soil usually has low concentrations of micronutrients such as Fe, Mn, Cu, and Zn [29]. Copper is an enzyme activator and disease fighter, and the Cu minimum value needed in the soil is 1.5 mg kg^{-1}, and a value higher than 4 mg kg^{-1} is excessive [30]. Copper and Zn affect each other availabilities to plants, and ideally soil Cu concentration should be half of Zn. Our results showed that after

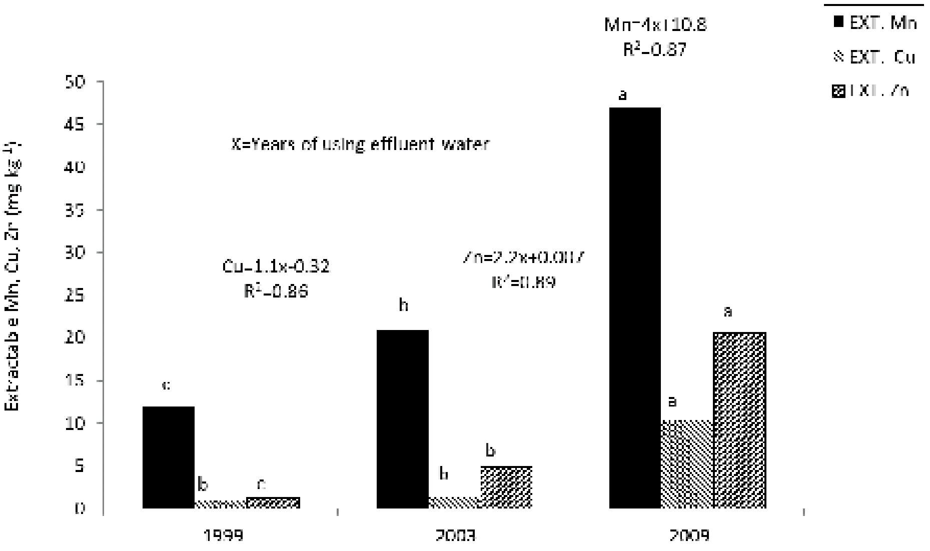

Figure 13. Effect of using effluent irrigation on soil extractable manganese, copper, and zinc. Different letters indicate significant differences within the parameter using LSD ($P < 0.05$).

9 years of effluent water, Cu and Zn concentrations were very high in this putting green soil; however, toxicity is not a concern here for both elements due to the nonacidic soil pH.

Moreover, extractable aluminum (Al) increased over time after using effluent water ($R^2 = 0.5$) (**Figure 14**), and the percent increase was 63% up to 142 mg kg^{-1}. These increases could be due to the effluent water use and could also be due to the soil aging and management practices. Toxic levels of Al are heavily dependent on the pH. In general, Al toxicity increases as soil acidity increases to a pH level of 4.8. In our study site, Al stayed bonded and not available to the plant.

A significant increase appeared in soil extractable boron (B) after the use of effluent water ($R^2 = 0.68$) (**Figure 15**), and the percent increase over time was 260% with an average rate of 0.06 mg kg^{-1} $year^{-1}$. These results are most likely due to effluent water use and are in agreement with the previous study for the same golf course fairway soil. The extractable B gradually increased ($R^2 = 0.56$) after using effluent water in fairway soils [9]. The criteria for B concentration in soils are as follows: shoot growth of sensitive plants could decline as soil B exceeds 0.5–1.0 mg kg^{-1}. Moderately sensitive plants would start to decline when soil B exceeds 1.0–2.0 mg kg^{-1}. Kentucky bluegrass can tolerate soil B concentration of 2.0–4.0 mg kg^{-1}, while tolerant grasses can tolerate soil B of 6–10 mg kg^{-1}. The effluent water used in this study contained about 0.2 mg L^{-1} boron (**Table 1**). Soil samples collected had a range from 0.2 to 0.7 mg kg^{-1} of B. This average level of soil B concentration was higher in 2009 compared to what was measured in 1999 (0.2 mg kg^{-1}), yet this range of B concentration was well below the toxic threshold for creeping bentgrass greens.

The same study was done previously on Heritage Golf Course fairways [9]. In comparison between the greens and the fairways in these two studies, we found that both green and fairway soil chemistry changed over time after nine years of using effluent water. In many categories, results were similar for the greens and the fairways. In both studies, soluble S was increased significantly due to the S burner mentioned before. Increases in Na concentration, B concentration, soil ESP, and Na available for release were similar between the two studies. Although SOM increased in both studies, CEC increased in the green soil but not in the

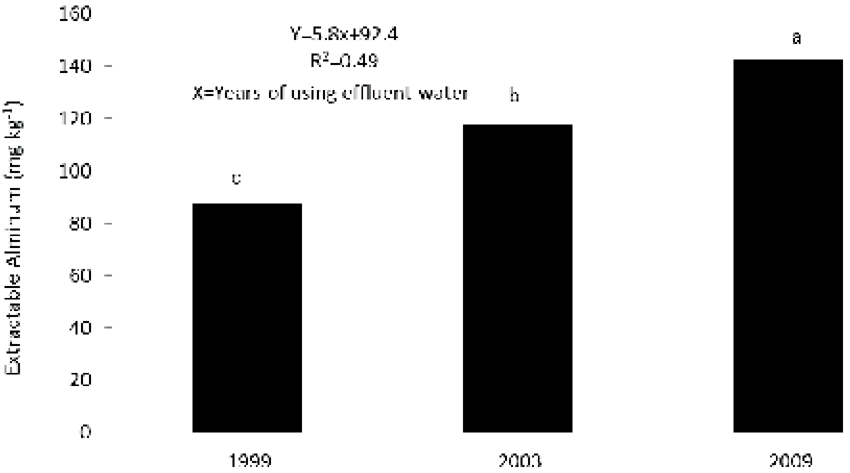

Figure 14. Effect of using effluent irrigation on soil extractable aluminum. Different letters indicate significant differences using LSD ($P < 0.05$).

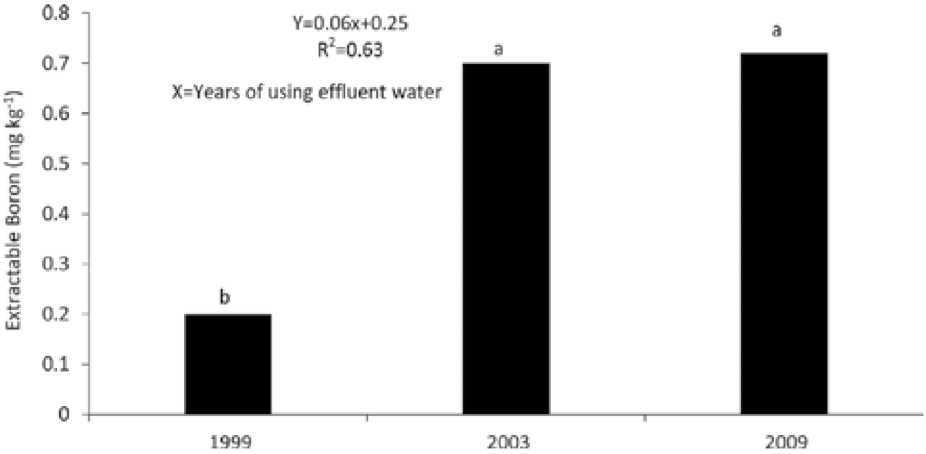

Figure 15. Effect of using effluent irrigation on soil extractable boron. Different letters indicate significant differences using LSD ($P < 0.05$).

fairway. In contrast, some soil parameters responded differently in the two studies. For example, significant increases in trace elements such as Cu, Zn, Mn, and Al were only observed in the green studies but not in fairways. Similarly, Fe concentration significantly increased in the greens but not in the fairways. These differences between the two studies could be due to the different soil type and structure in the greens and the fairways. Further studies are needed to determine if the change of soil parameters would continue over time.

4. Conclusion

Soil test data for the Heritage Golf Course, which uses effluent water for irrigation, showed that the soil's chemical characteristics changed over time. Soil organic matter increased from 0.12 to 1.5%. Soil CEC was significantly increased by as much as double over nine years. Exchangeable Ca, Mg, K, and Na also increased by 198, 116, 148, and 452%, respectively, over nine years of effluent water irrigation. More than fourfold increase in Na could affect the soil structure and lead to a lack of aeration for roots. However, the application of gypsum can be used to minimize this effect. In addition, a significant increase over time was shown for extractable Fe, Mn, Cu, Zn, and Al.

In general, most of the chemical parameters have significantly changed over nine years of effluent water irrigation; however, not all changes are necessarily due to the use of effluent water. Some changes in soil chemistry could be the result of golf course management practices, such the use of an S-burning unit, which increased soluble S in the irrigation water. In addition, these greens are relatively young (built in 1998), they need time to become mature, and their soil becomes stable over time. However, increases in other elements such as sodium, boron, and phosphate could be due to the use of effluent water. The greater increases in SOM and estimated N release, and increases in trace elements such as Cu, Zn, and Mn could also be the result of using effluent water for irrigation.

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Water Productivity Modeling by Remote Sensing in the Semiarid Region of Minas Gerais State, Brazil

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Abstract

This chapter aimed to demonstrate the potential of monitoring water and vegetation parameters by combining weather and satellite measurements in mixed agroecosystems in the semiarid region of the northern Minas Gerais state, Southeast Brazil. Soil moisture indices and water productivity components were quantified with Landsat 8 images under different hydrological conditions along the year 2015. The surface resistance to the water fluxes (r_s) performed better than the ratio of actual to the reference evapotranspiration (ET_r) to detect soil moisture conditions. The mean pixel values for actual evapotranspiration (ET), biomass production (BIO), and water productivity based on evapotranspiration (WP), for irrigated crops (IC), ranged respectively from 2.5 ± 1.3 to 4.1 ± 1.6 mm d^{-1}; 78 ± 62 to 132 ± 64 kg ha^{-1} d^{-1}; and from 2.2 ± 0.8 to 3.3 ± 0.9 kg m^{-3}. The corresponding ranges for natural vegetation (NV) were 0.1 ± 0.2 to 1.9 ± 1.3 mm d^{-1}; 1 ± 1 to 44 ± 42 kg ha^{-1} d^{-1}, and 0.6 ± 0.3 to 1.8 ± 0.8 kg m^{-3}. The incremental values, resulting from the replacement of natural species by agricultural crops, were respectively 2.7 mm d^{-1} and 83 kg ha d^{-1}. However, this replacement increased water productivity based on evapotranspiration (WP) by 264% during the studied year, what should be considered in land use and climate change studies in the Brazilian semiarid region.

Keywords: SAFER, SUREAL, soil moisture, evapotranspiration, biomass production

1. Introduction

In the semiarid region of the northern Minas Gerais state, Southeast Brazil, the availability of water resources for irrigation is responsible for the rural economy growth. The main commercial crops are fruits and sugar cane; however, one of the main consequences of this development is that other water users are competing with those from the agricultural sectors. The Jaíba irrigation scheme has a total area of 107,600 ha, being 65,800 ha irrigable, involving Jaíba and Matias Cardoso counties. The Gorotuba irrigation scheme has a total area of 11,280 ha, from which 4886 are irrigable, involving the counties of Janaúba, Nova Porteirinha, and Riacho dos Machados [1].

The irrigation schemes make the north of Minas an important agricultural growing region, because of the rapid development of the irrigation technologies. Under the actual climate and land-use change scenarios in the Brazilian semiarid region, the use of remote sensing from satellites, for quantifying the large-scale soil moisture and water productivity components in mixed agroecosystems, is strongly relevant. These knowledges provide valuable information for the water resource conservation practices without lowering the agricultural production. To meet this goal, there is the need for large scale quantifying both actual evapotranspiration (ET) and biomass production (BIO).

Actual evapotranspiration (ET) is critically important because of its relation with yield in all agroecosystems. On the one hand, it is the main water use for agriculture. On the other hand, increase in evapotranspiration rates results in less water availability for ecological and human uses in hydrological basins. The difficulties of acquiring large-scale water fluxes throughout field measurements in semiarid environments highlighted the use of remote sensing from satellites, together with agrometeorological stations [2, 3].

The Simple Algorithm for Evapotranspiration Retrieving (SAFER) model, for energy radiation and energy balance accounting, was developed and validated in the Brazilian semiarid region through simultaneous Landsat and field measurements, involving strong contrasting hydrological conditions and agroecosystem types during several years [4, 5].

Remote sensing from satellites is also an effective tool for large-scale biomass production estimations. The radiation use efficiency (RUE) model proposed by Monteith [6] has acceptable accuracy for this purpose, providing spatial and temporal information of vegetation locations and plant status [7].

A third model, the Surface Resistance Algorithm (SUREAL), was elaborated to calculate the surface resistance to water fluxes (r_s), a soil moisture index, with field and Landsat data [4, 5], for classifying mixed agroecosystems into irrigated crops (IC) and natural vegetation (NV) [8].

All the referred models are applied together with a net of agrometeorological stations in this chapter to retrieve large-scale water and vegetation indices, highlighting the combination of remote sensing algorithms as suitable tools for using together with weather data. The study aimed to apply these tools for subsidizing large-scale water productivity assessments in irrigated crops and natural vegetation under the semiarid conditions of Minas Gerais state, Southeast Brazil.

2. Materials and methods

2.1. Study area and data set

Figure 1 shows the location of the study area with the county divisions and the agrometeorological stations used in the semiarid region of the north of Minas Gerais state, Southeast Brazil.

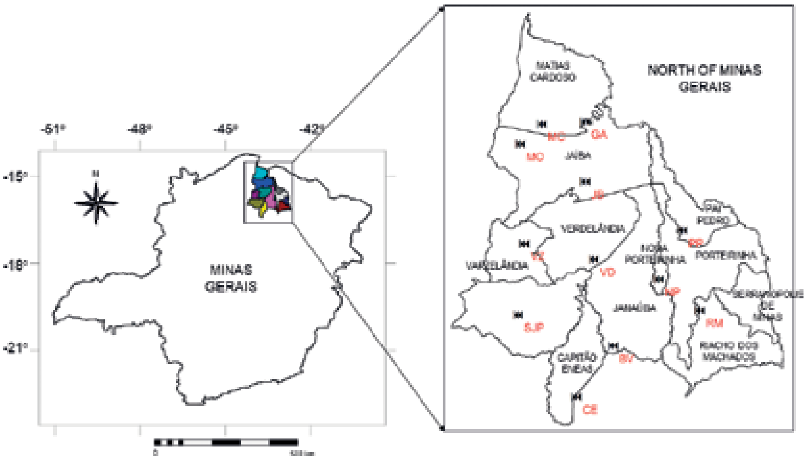

Figure 1. Location of the study area and agrometeorological stations inside the counties under the semiarid conditions of the north of Minas Gerais state, Southeast Brazil.

The agrometeorological stations are Mocambinho (MC), Matias Cardoso (MC), Gameleiras (GA), Jaíba (JB), Varzelândia (VZ), Verdelândia (VD), Pai Pedro (PP), Nova Porteirinha (NP), São João da Ponte (SJP), Riacho dos Machado (RM), Bela Vista (BV), and Capitão Eneas (CE).

The predominant vegetation cover in the semiarid region of the northern Minas Gerais state, Southeast Brazil, is classified as "Cerrado," "Caatinga," and transitions [9], and the main hydrological basins are São Francisco and Jequitinhonha [10].

According to Lumbreras et al. [11], long-term rainfall is below 900 mm yr.$^{-1}$, concentrated in the first and the last 3 months of the year. Thermal conditions are characterized by high air temperature (T_a), with averages of 24°C and maximums between 31 and 32°C, occurring from September to October, when the sun is around the zenith position in the region. The coldest period is from June to July, solstice period in the Southern hemisphere, when the minimums are from 14 to 17°C.

2.2. Large-scale soil moisture and water productivity modeling

The Landsat 8 images involved the orbit 218 and the points 70 and 71, which mosaics covered different hydrological conditions along the year 2015, represented by the Days of the Year (DOY) 019 (January 19), 163 (June 12), 259 (September 16) and 307 (November 03). **Figure 2** shows the steps for modeling the soil moisture indices and water productivity components throughout the Simple Algorithm for Evapotranspiration Retrieving (SAFER), Radiation Use Efficiency (RUE), and Surface Resistance Algorithm (SUREAL) models.

According to **Figure 2**, from the Digital Numbers (DN), the spectral radiances for each band (L_{band}) are calculated:

$$L_{band} = aDN + b \tag{1}$$

where a and b are regression coefficients given in the metadata file [12].

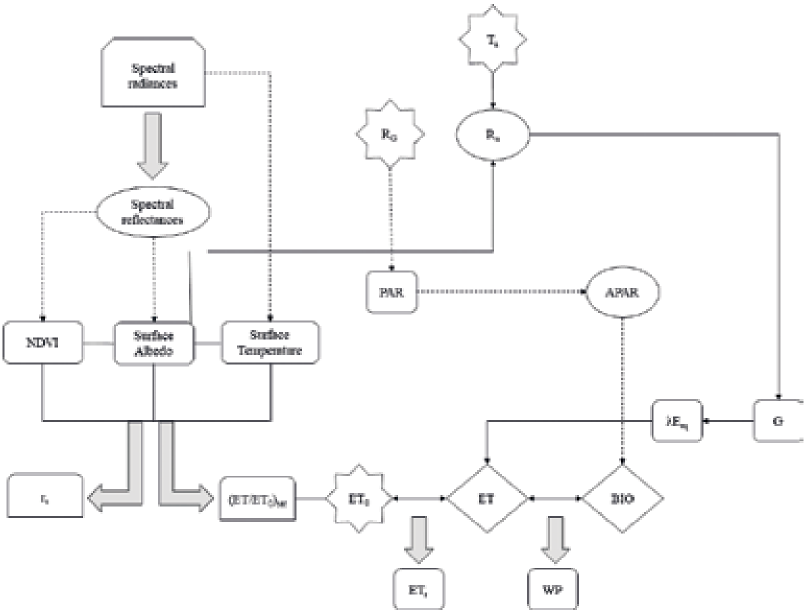

Figure 2. Flow chart for modeling soil moisture indices and water productivity components throughout application of the Simple Algorithm for Evapotranspiration Retrieving (SAFER), Radiation Use Efficiency (RUE), and Surface Resistance Algorithm (SUREAL) models to Landsat 8 images together with agrometeorological data.

The albedo at the top of the atmosphere for each band (αt_{band}) of the satellite sensor was calculated as:

$$\alpha\, t_{band} = \frac{L_{band}\, \pi d^2}{Rt_{band} \cos\varphi} \tag{2}$$

where L_{band} is in W m^{-2} sr^{-1} μm^{-1}, d is the relative earth-sun distance, Rt_{band} is the mean solar irradiance at the top of the atmosphere for each band (W m^{-2} μm^{-1}), and φ is the solar zenith angle [3].

Following Teixeira et al. [3], the broadband albedo at the top of the atmosphere (αt) was calculated as the total sum of the different narrow-band αt_{band} values according to the weights for each band (w_b).

$$\alpha t = \sum w_{band}\, \alpha t_{band} \tag{3}$$

where the w_{band} values were computed as the ratio of the amount of the incoming shortwave radiation from the sun at the top of the atmosphere in a particular band and the sum for all the bands.

The spectral radiances from the thermal bands 10 (L_{10}) and 11 (L_{11}) were used to calculate the radiometric temperatures (T_{band}) applying the Plank's law:

$$T_{band} = \frac{K_2}{\ln\left(\frac{K_1}{L_{band}} + 1\right)}, \tag{4}$$

where K_1 (774.89 and 480.89) and K_2 (1321.08 and 1201.14) the conversion coefficients for the bands 10 and 11, respectively.

The average T_{band} value from the two bands was considered as the brightness temperature (T_{bright}); however, conditional functions were used when one of the bands 10 or 11 presented pixel value problems to retrieve only one band Plank's result for T_{bright}.

Both αt and T_{bright} were corrected atmospherically for acquiring the albedo (α_0) and temperature (T_0) surface instantaneous values, by regression equations determined from previous simultaneous Landsat and field measurements. Other regressions between the instantaneous and daily values were also applied to upscale the satellite overpass to the 24-h α_0 and T_0 values [3].

The Normalized Difference Vegetation Index (NDVI) is a measure of the vegetation amount at the surface:

$$\mathrm{NDVI} = \frac{\alpha t_{(nir)} - \alpha t_{(red)}}{\alpha t_{(nir)} + \alpha t_{(red)}} \tag{5}$$

where αt_{nir} and αt_{red} represent the albedo at the top of the atmosphere over the ranges of wavelengths in the near infrared (subscript *nir*) and red (subscript *red*) regions of the solar spectrum, which for Landsat 8 satellite are the bands 5 and 4, respectively.

The satellite overpass (subscript *sat*) values for the ratio of actual evapotranspiration (ET) to the reference evapotranspiration (ET_0) were modeled as [5]:

$$\left(\frac{ET}{ET_0}\right)_{sat} = \exp\left[a_{sf} + b_{sf}\left(\frac{T_0}{\alpha_0\,\mathrm{NDVI}}\right)\right] \tag{6}$$

where a_{sf} and b_{sf} are regression coefficients of 1.8 and −0.008, for the Brazilian semiarid conditions.

Eq. 6 does not work for water bodies (i.e., NDVI <0). In these situations, the concept of equilibrium evapotranspiration (ET_{eq}) is incorporated into the Simple Algorithm for Evapotranspiration Retrieving (SAFER) algorithm [13], applying conditional functions to negative NDVI values. Then, the large-scale actual evapotranspiration (ET) values are obtained as:

$$ET = \left(\frac{ET}{ET_0}\right)_{sat} ET_0 \text{ or } 0.035\left(\frac{s(R_n - G)}{s + \gamma}\right) \tag{7}$$

where s is the inclination of the curve relating the saturation vapor pressure (e_s) and the air temperature (T_a), R_n is the net radiation, G is the ground heat flux, and γ is the psychrometric constant.

Net radiation (R_n) can be described through the 24-h values of net shortwave radiation, with a correction term for net longwave radiation [4]:

$$R_n = (1 - \alpha_0)R_G - a_L\tau \tag{8}$$

where a_L is the regression coefficient of the relationship between net long wave radiation and atmospheric transmissivity (τ) on a daily scale.

For ground heat flux (G), the equation derived by Teixeira [5] was used:

$$\frac{G}{R_n} = a_G \exp(b_G \alpha_0) \tag{9}$$

where a_G and b_G (3.98; −25.47) are the regression coefficients.

A soil moisture index (ET_r) is considered by recalculating the ratio of the actual (ET) to reference (ET_0) evapotranspiration on a daily scale:

$$ET_r = \frac{ET}{ET_0} \tag{10}$$

For biomass production (BIO) calculations, the radiation use efficiency (RUE) model was used, introducing the soil moisture effects through the daily ratio of actual to reference evapotranspiration (ET_r):

$$BIO = \varepsilon_{max} ET_r PAR_{abs} 0.864 \tag{11}$$

where ε_{max} is the maximum radiation efficiency use, PAR_{abs} is the absorbed photosynthetically active radiation, and 0.864 is a unit conversion factor.

The absorbed photosynthetically active radiation (PAR_{abs}) was estimated as function of the Normalized Difference Vegetation Index (NDVI) and the incident photosynthetically active radiation (PAR_{inc}), which in turn is considered a fraction of the global solar radiation (R_G):

$$PAR_{abs} = (a_{fr} NDVI + b_{fr}) PAR_{inc} \tag{12}$$

where the coefficients a_{fr} and b_{fr} were considered 1.257 and −0.161 [14].

As another index, the surface resistance to the water fluxes (r_s) was used to picture the soil moisture conditions, but also for classifying the vegetation, into irrigated crops (IC) and natural vegetation (NV), throughout the surface resistance algorithm (SUREAL) model [5]:

$$r_s = \exp\left[a_r\left(\frac{T_0}{\alpha_0}\right)(1 - NDVI) + b_r\right] \tag{13}$$

where a_r and b_r are the regression coefficients of 0.04 and 2.72 for the Brazilian semiarid conditions.

3. Results and discussion

3.1. Large-scale weather conditions

Figure 3 presents the tendencies of the fortnight mean pixel values for precipitation (P) and reference evapotranspiration (ET_0) resulted from the weather interpolation process in the study area, including the periods before, during, and after the satellite image acquisitions. Weather conditions during these periods will affect the image process results.

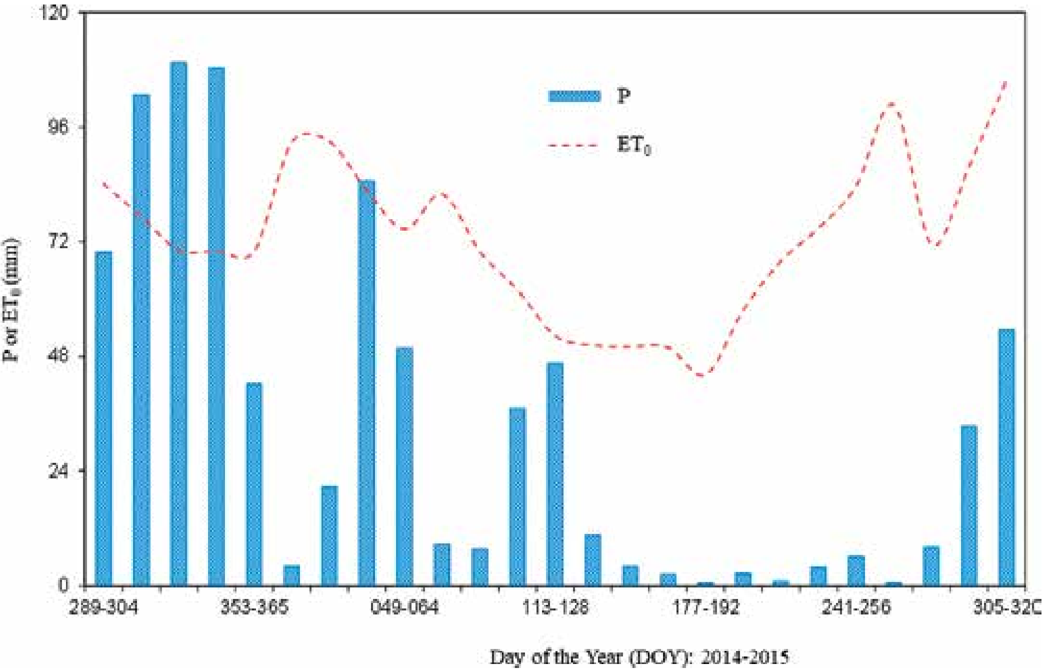

Figure 3. Climatic water balance components in the semiarid region of the northern Minas Gerais state, involving the fortnight periods from 2014 to 2015, before, during, and after the image acquisitions: precipitation (P) and reference evapotranspiration (ET_0).

Because of the semiarid characteristics of the study region and the proximity of the equator, precipitation (P) was much more variable than reference evapotranspiration (ET_0). Rainfall concentrations were at the start and at the end of the years, in agreement with Lumbreras et al. [11]. The driest period, with precipitation (P) fortnight values below 5 mm, was from Day of the Year (DOY) 160 to 289 in 2015, lower than 10% of the reference evapotranspiration (ET_0). However, one can see other natural water scarcity events, one at the start of January and from Day of the Year (DOY) 064 to 097, even inside the normal rainy season conditions of the region.

Regarding the reference evapotranspiration (ET_0) values, the largest atmospheric demands were at the end of 2015, when the fortnight values were higher than 80 mm. Under these situations, the sun was around its zenith position with the sky presenting low cloud cover. Under the conditions of high both precipitation (P) and reference evapotranspiration (ET_0), during the start and at the end of year, all agroecosystems, irrigated crops (IC) and natural vegetation (NV) were in favor for large actual evapotranspiration (ET) and biomass production (BIO) rates.

3.2. Large-scale soil moisture indices

Figure 4 shows the spatial distribution for the actual to reference evapotranspiration ratio (ET_r) and its daily average values, involving different hydrological conditions and agroecosystems along the year 2015, in the semiarid region of the north of Minas Gerais state, Southeast Brazil.

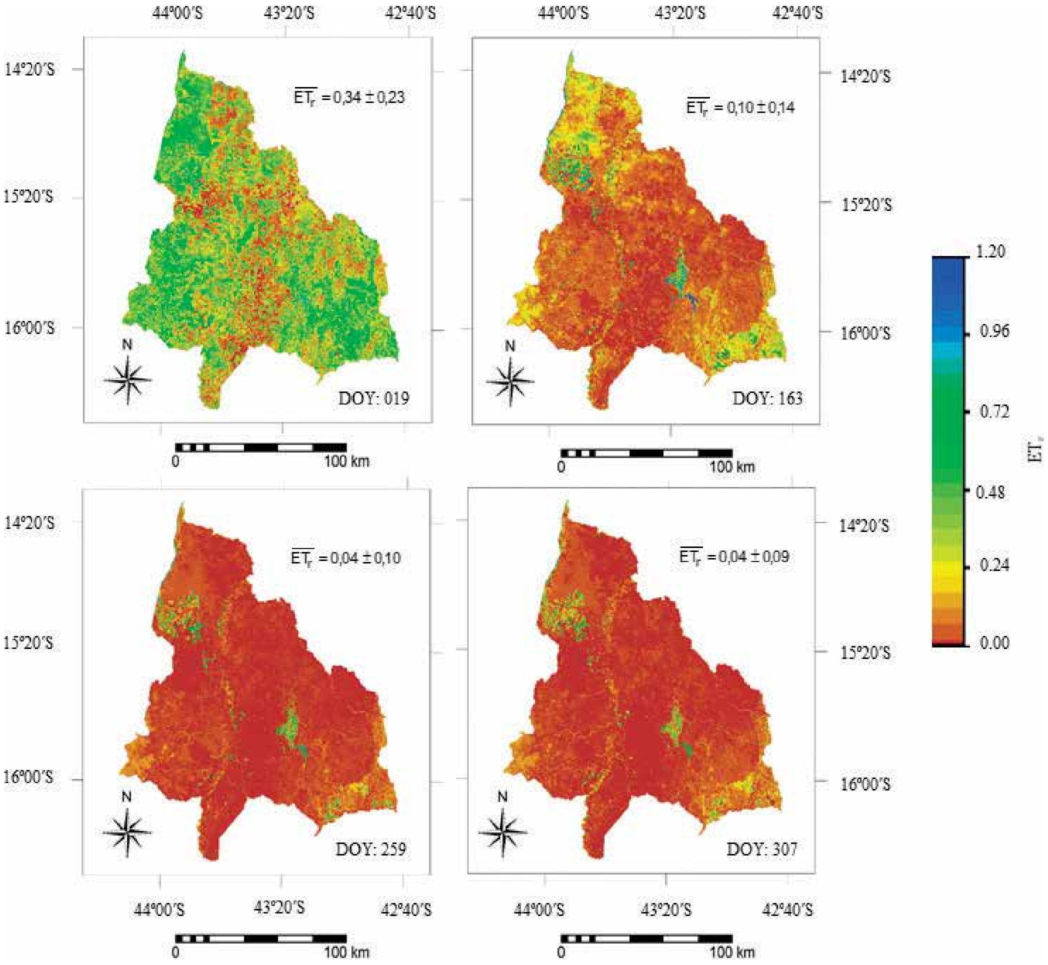

Figure 4. Spatial distribution of the daily values for the ratio of actual evapotranspiration – ET to the reference evapotranspiration – ET_0 (ET_r), involving different hydrological conditions and agroecosystems along the year 2015, in the north of Minas Gerais state, Southeast Brazil. DOY is the Day of the Year, and the over bars mean averages showed together with the standard deviation (SD).

The spatial and temporal variations, the actual (ET) to reference evapotranspiration (ET_0) ratio (ET_r), along the year 2015 are evident, confirming the sensibility of the Simple Algorithm for Evapotranspiration Retrieving (SAFER) model to picture the soil moisture involving different hydrological conditions and agroecosystems. The spatial variations of this ratio are much strongly noticed when comparing the images representative of the rainy period (DOY 027, January 29) when some well irrigated areas presented values above 1.00, against that for the driest one of DOY 307 (November 03), when some pixels reach to 0.00 values in natural species (**Figures 3** and **4**). The highest values for Jaíba, Nova Porteirinha, and Riacho dos Machados counties during the climatically driest periods (**Figures 1** and **4**) may be attributed to largest concentrations of irrigated areas.

In well-irrigated crops, the actual to reference evapotranspiration ratio (ET_r) values, called in this case the crop coefficient (K_c), may be used for estimating the water requirements at different spatial scales [15]. On the other hand, in natural vegetation, this ratio characterizes the degree of the water stress in the plant root zones [16].

In a temperate desert steppe of the Inner Mongolia, China, the seasonal actual to reference evapotranspiration ratio (ET_r) ranged from mean daily values of 0.16 to maximum of 0.75 [17], similar to several situations of the current study. However, Lu et al. [16], in the same Chinese region, found this ratio higher than 1.00 for six different ecosystems, while it was inside a range from 0.47 to 0.92 in a non-irrigated pasture site in Florida, USA [18].

The most important variables for the actual to reference evapotranspiration ratio (ET_r) variations in a reed marsh in the Northeast China were attributed to air temperature, air humidity, and the available energy [19]. In the Brazilian semiarid conditions, previous rainy seasons were the most significant reason for the highest values of this ratio, increasing the soil moisture in the subsequent periods. However, the values of this soil moisture index in natural ecosystems also depend on the stomatal regulation and plant adaptation to water scarcity conditions [20].

In this chapter, the surface resistance to the water fluxes (r_s) is considered for both, being a candidate to picture the soil moisture conditions and to classify the agroecosystems into irrigated crops (IC) and natural vegetation (NV). As lower are its values, higher is the root zone moisture [3].

Figure 5 shows the spatial distribution for the surface resistance to water fluxes (r_s) and its average daily values, involving different hydrological conditions and agroecosystems along the year 2015, in semiarid region of the north of Minas Gerais state, Southeast Brazil.

The spatial and temporal variations of the surface resistance to water fluxes (r_s) are also clear along the year 2015, confirming the sensibility of the Surface Resistance Algorithm (SUREAL) model for detecting differences in soil moisture conditions among agroecosystems under semiarid conditions. As in the case of the actual to reference evapotranspiration ratio (ET_r), the spatial soil moisture differences are also strongly noticed comparing the representative images for the rainy period (DOY 019–January 19) against that for the driest conditions (DOY 307–November 03). However, it is clear that the surface resistance to water fluxes (r_s) detects the soil moisture differences stronger than the actual to reference evapotranspiration ratio (ET_r) when analyzing the images of DOY 259 (September 19) and 307 (November 03) from **Figures 4** and **5**.

Then, the surface resistance to water fluxes (r_s) image during the driest conditions of DOY 259 was taken for the vegetation classification. In this image, pixel values below 800 s m^{-1} and the Normalized Difference Vegetation Index (NDVI) above or equal to 0.30 were considered irrigated crops (IC), while those with values between 1000 and 10,000 s m^{-1} and the Normalized Difference Vegetation Index (NDVI) below 0.30 were considered natural vegetation (NV). The high end of this last range was included to filter rocks and buildings [3]. The lowest values of the surface resistance to water fluxes (r_s) in vegetation indicate good soil moisture conditions, while the highest ones are related to water stress in all agroecosystems.

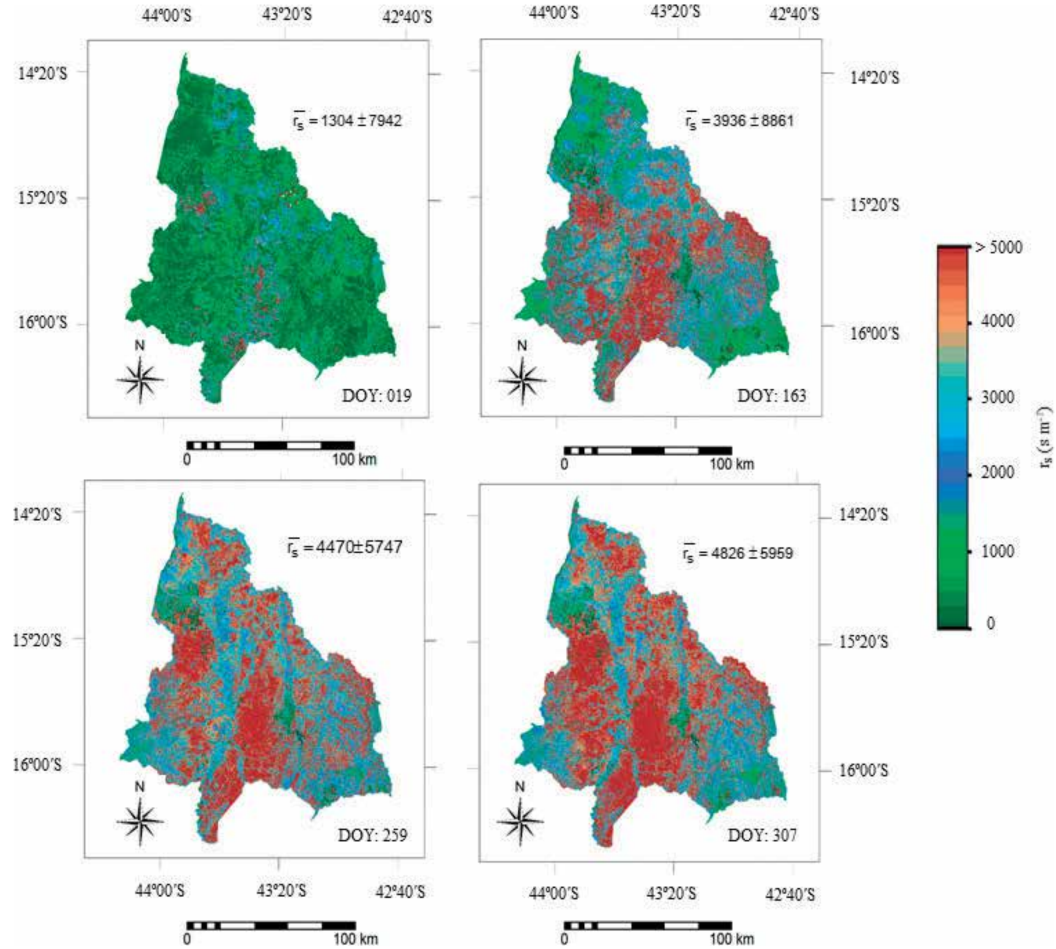

Figure 5. Spatial distribution for the surface resistance to water fluxes (r_s), under different hydrological conditions and agroecosystems along the year 2015, in the north of Minas Gerais state, Southeast Brazil. DOY is the Day of the Year, and the over bars means averages showed together with standard deviation (SD).

3.3. Large-scale water productivity parameters

Figure 6 shows the spatial distribution and the average daily values for actual evapotranspiration (ET) and biomass production (BIO) for irrigated crops (IC) and natural vegetations (NV), under different hydrological conditions along the year 2015, in the north of Minas Gerais state, Southeast Brazil.

The spatial and temporal variations for actual evapotranspiration (ET) (**Figure 6a**) and biomass production (BIO) (**Figure 6b**) are both strong. This is noticed mainly when comparing the wettest conditions (represented by the image of DOY 019—January 19) with the driest ones (represented by the image of DOY 259—September 16), where the pixels with the high values represent irrigated crops (IC). The largest rates for both water productivity parameters occurred during the

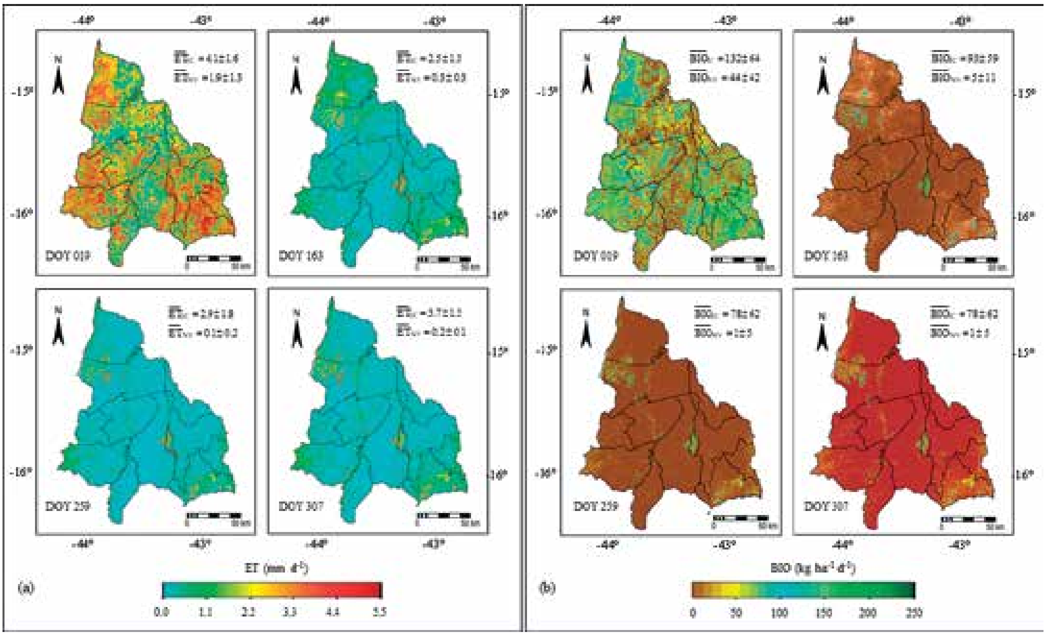

Figure 6. Spatial distribution and the daily average values for the water productivity parameters, under different hydrological conditions along the year 2015, in the north of Minas Gerais state, Southeast Brazil. (a) Actual evapotranspiration (ET) and (b) biomass production (BIO). DOY is the Day of the Year and the over bars means averages for irrigated crops (IC) and natural vegetation (NV) showed together with standard deviations (SD).

rainy period, when the accumulated precipitation (P) favored the natural species, while besides the rainfall water supply, irrigated crops were beneficed with supplementary irrigation.

The lowest actual evapotranspiration (ET) and standard deviation (SD) values for irrigated crops (IC) were soon after the rainy period, conditions represented by the image of DOY 163 (June 12). For biomass production (BIO), they were during the climatically driest conditions, represented by the image of DOY 259 (September 16), however with the lowest spatial variations in November (DOY 307). Considering the natural vegetation ecosystem (NV), the highest both actual evapotranspiration (ET) and biomass production (BIO) values occurred during the rainy period, represented by the image of DOY 019 (January 19), while the lowest ones were during the climatically driest period (DOY 259, September 16), because of the low soil moisture conditions promoting short vegetative development of natural species. Under these last conditions, the native plants are in dormancy stage, closing stomata what limit both transpiration and photosynthesis, and in general, crops are regularly daily irrigated, increasing the water productivity parameters.

The average pixel values for actual evapotranspiration (ET) and biomass production (BIO), in irrigated crops (IC), ranged respectively from 2.5 ± 1.3 to 4.1 ± 1.6 mm d^{-1} and from 78 ± 62 to 132 ± 64 kg ha^{-1} d^{-1}. The corresponding ranges for natural vegetation (NV) were 0.1 ± 0.2 to 1.9 ± 1.3 mm d^{-1} and de 1 ± 1 to 44 ± 42 kg ha^{-1} d^{-1}. Leivas et al. [2] reported maximum actual evapotranspiration (ET) values of 3.5 ± 1.0 mm d^{-1} in the Jaíba irrigation scheme. In the Petrolina/Juazeiro agricultural growing region, under the semiarid conditions of the São

Francisco river basin, Teixeira et al. [7] found maximum values of biomass production (BIO) of 100 and 46 kg ha^{-1} d^{-1} in irrigated crops (IC) and natural vegetation (NV) agroecosystems, respectively. These differences, regarding the results in this chapter, may be related, in part, to the lower spatial resolution of the MODIS images used in the previous studies, in comparison with that for the Landsat 8 in the current research.

While along the year, the values for actual evapotranspiration (ET) and biomass production (BIO) were progressively declining, reaching close to zero in November (DOY 307) in the natural vegetation (NV) ecosystem, in irrigated crops (IC), they were always above 2.5 mm d^{-1} and 78 kg ha d^{-1}, respectively. In an annual scale, the incremental rates resulting from the replacement of natural species by irrigated crops were 2.7 mm d^{-1} and 83 kg ha d^{-1}.

The largest both actual evapotranspiration (ET) and biomass production (BIO) were for the Jaíba and Matias Cardoso counties (**Figures 1** and **6**), because of the irrigation water availability in the Jaíba irrigation scheme, from the São Francisco river. Highlights in the region are also for Nova Porteirinha and Janaúba counties, inside the Gorotuba irrigation scheme, but in this last case, the dam Bico da Pedra is the water source. These irrigation schemes concentrate mainly irrigated fruit cops and sugar cane. The Riacho dos Machados county also presents some areas with high actual evapotranspiration (ET) and biomass production (BIO), being these large values probably related to cattle and family farms, with the main water sources from the Vacaria River and the Samambaia Stream.

Figure 7 shows the spatial distribution and the average daily values for the water productivity based on evapotranspiration (WP) for irrigated crops (IC) and natural vegetation (NV), under different hydrological conditions along the year 2015, in the north of Minas Gerais state, Southeast Brazil.

In the case of the water productivity based on evapotranspiration (WP), considered as the ratio of biomass production (BIO) to actual evapotranspiration (ET), the largest values and spatial variations for irrigated crops (IC) were in June (representative image of DOY 163), period of optimum crop root-zone moisture conditions, happening soon after the rainy period. On the other hand, inside the rainy period (conditions represented by the image of DOY 019), happened the highest values for the natural vegetation (NV) ecosystem. The large spatial variations indicated different soil moisture and vegetation conditions in natural species and heterogeneity on crop stages in irrigated crops. More uniformity on the values of water productivity based on evapotranspiration (WP) was for the natural vegetation (NV) ecosystem, evidenced by the lower standard deviations when compared to the irrigated crops (IC) agroecosystem.

The seasonal values of the water productivity based on evapotranspiration (WP) for the irrigated crops (IC) agroecosystem ranged from 2.2 ± 0.8 to 3.3 ± 0.9 kg m^{-3}. The corresponding range for the natural vegetation (NV) ecosystem was from 0.6 ± 0.3 to 1.8 ± 0.8 kg m^{-3}. These values when multiplied by the harvest index (HI) give the crop water productivity (CWP). Reported harvest index (HI) values were around 0.60 and 0.80 for vineyards and mango orchard under the semiarid conditions of Northeast Brazil, retrieving crop water productivity (CWP) values of 2.8 and 3.4 kg m^{-3} [21]. The maximum values for water productivity based on evapotranspiration (WP) in the current study when multiplied by these harvest indexes (HI) are lower, being the probable reason the water allocation restriction for irrigation schemes during the drought events in the year 2015.

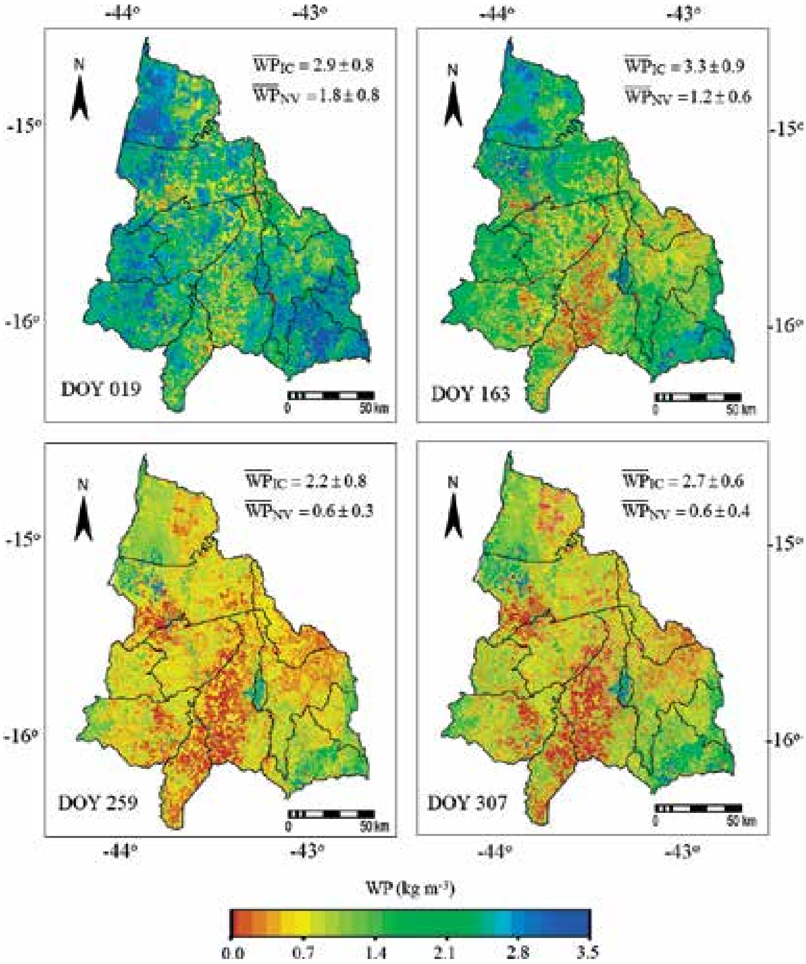

Figure 7. Spatial distribution of the daily values for the water productivity based on evapotranspiration (WP), under different hydrological conditions along the year 2015, in the north of Minas Gerais state, Southeast Brazil. DOY is the Day of the Year and the over bars means averages in irrigated crops (IC) and natural vegetation (NV) agroecosystems, showed together with the standard deviation (SD).

4. Conclusions

The coupled use of Landsat 8 images and a net of agrometeorological stations allowed the large-scale quantification of the water productivity parameters, under different hydrological conditions and agroecosystems during the year 2015 in the north of Minas Gerais state, Southeast Brazil. The analyses may subsidize a better understanding of the soil moisture, actual evapotranspiration (ET) and biomass production (BIO) dynamics, important water policy issues under the actual climate and land-use change conditions in the Brazilian semiarid region.

Vegetated surfaces were classified into irrigated crops (IC) and natural vegetation (NV), highlighting the rainy period as the one with the highest actual evapotranspiration (ET) and biomass production (BIO) rates for both irrigated crops (IC) and natural vegetation (NV) agroecosystems.

However, the largest water productivity based on evapotranspiration (WP) values, considered as the ratio of biomass production (BIO) to actual evapotranspiration (ET), was during the rainy period for the natural species, while for the irrigated crops they were soon after this period.

The remote sensing model algorithms applied here demonstrated enough accuracy to be implemented in rational water resource policies in the Brazilian semiarid region experiencing climate and land use changes, once having available spatially distributed agrometeorological data. From the sensibility of the models to detect soil moisture conditions, the results revealed confidence for later applications of monitoring water and vegetation indices, quantifying the effects of water scarcity along the years.

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Arid environments are basically associated with water scarcity. Therefore, soils will have an extremely low moisture level to support plant and animal life as well as human social life. Sustainability is the long durability of systems and processes within various adapted environmental conditions. Recently, systematic scientific studies on arid environments and sustainability have become more attractive, critical, and sound than the previous years. Sharing such experiences related to different environmental circumstances will absolutely help scientists and decision-makers to have better interpretation of their own environment. By learning lessons, appropriate, fast, and effective approaches require to implement for overwhelming such problems. Such actions will certainly lead to more secure and sustainable environments for plant, animal, and human life.

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