Heliyon 12 (2026) e45122

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Areas covered by cactus (*Opuntia* spp.) and methods to assess their biomass and carbon sequestration – A review

Kenneth T. Oduor [a,1,*], Jose C.B. Dubeux Jr. [a], Igor L. Bretas [a,2], Luana M. D. Queiroz [a,3]

[a] University of Florida, North Florida Research and Education Center-Marianna, 3925 Highway 71, Marianna, FL, 3925 USA

ARTICLE INFO

Keywords:
Cactus biomass
Carbon stocks
Carbon sink
Climate change

ABSTRACT

Increasing carbon sequestration in terrestrial systems is one potential solution to mitigate global warming. Cactus can withstand drought to produce biomass, making it an important carbon sink. Accurately estimating carbon stocks is crucial for identifying and promoting cactus production systems with the highest capacity for carbon sequestration. Although several methods for estimating biomass and carbon stocks are available in the literature, their application in cacti is still limited due to their unique structural characteristics, which require modified approaches. This review presents diverse cactus land uses and their potential to sequester carbon. We also provide the available methods for estimating carbon stocks and sequestration applied to cactus and future considerations. Typical land uses of cactus include fruit orchards, intensive systems for fodder, and rangelands. Aboveground biomass in cactus is mostly estimated using destructive methods and allometric equations. The use of remote sensing techniques is still limited and needs to be fully leveraged, given its robustness in covering vast areas such as those in rangelands. The Eddy covariance towers can also provide long-term ecosystem measurements of carbon fluxes, including carbon sequestration rates. Soil organic carbon can be estimated using the chronosequence technique and repeated measurements. However, the rate and extent of soil organic carbon can be determined using the fine root input, mean residence time, and root turnover methods. Although the reviewed methods have great application in cactus, developing a standardized methodological framework will enable more accurate projections of carbon sequestration potential under different land uses and management approaches. Similarly, future research actions are necessary to validate these methods under different land uses.

1. Introduction

Drylands cover 40% of the global terrestrial surface [1] and contribute approximately 16% of the global soil organic carbon (SOC) pool [2]. This storage is vital for mitigating climate change, as soil organic carbon acts as a significant carbon sink. Furthermore, the health of dryland ecosystems is partly linked to their SOC levels, which influence vegetation cover, soil fertility, and overall

* Corresponding author.
E-mail addresses: Kenneth.oduor@ufl.edu, tembeken@gmail.com (K.T. Oduor).
[1] Center for Water Resources, College of Agriculture and Food Sciences, Florida A&M University, Tallahassee, FL 32307, USA.
[2] Embrapa Meio-Norte, Parnaíba-PI, 64200-000, BR-343, km 35, zona rural, Brazil.
[3] University of Wisconsin, Madison, WI, USA.

https://doi.org/10.1016/j.heliyon.2026.e45122
Received 8 June 2024; Received in revised form 16 June 2026; Accepted 17 June 2026
Available online 16 July 2026
2405-8440/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

biodiversity [3]. With climate change and rising temperatures, cacti are becoming increasingly important for enhancing carbon sequestration in drylands due to their adaptation [4]. According to Jardim et al. [5], cactus is a potential carbon sink with an estimated net ecosystem CO_2 exchange of −377 g C m^{-2} $year^{-1}$, and gross primary production of 881 g C m^{-2} $year^{-1}$. Establishing them is, therefore, a promising strategy for mitigating climate change.

Cactus (*Opuntia* spp.) is well adapted to arid and semi-arid regions largely due to its Crassulacean Acid Metabolism (CAM) photosynthetic pathway [6]. This specialized pathway enables them to fix carbon efficiently under water-limited conditions, minimizing water loss while maintaining high biomass productivity. Other drought-adaptation traits of cacti include a protective epidermis with a thick, waxy, waterproof cuticle and a shallow root system, enabling the plant to make use of light rains [7]. These adaptations distinguish cacti from other plant species, making them valuable contributors to dryland carbon cycling. In addition to carbon sequestration, *Opuntia* spp. can produce food, fodder, bioenergy, and other ecosystem services [7]. Given the diverse land uses and ecosystem services provided by *Opuntia* spp., understanding how different cactus production systems contribute to biomass accumulation and carbon storage is essential for accurately assessing their role in carbon sequestration and climate change mitigation.

Aboveground and belowground plant biomass are commonly used to estimate carbon stocks and sequestration potential in terrestrial ecosystems. The methods developed to quantify biomass, carbon stocks, and soil organic carbon (SOC) dynamics in other plant systems can also be applied to cactus-based ecosystems, although modifications are often required. This is because cacti possess unique structural characteristics, including segmented stems (cladodes), succulent tissues with high water content, variable growth forms, and shallow, widely distributed root systems, which can influence biomass measurements and carbon assessments. Consequently, the direct application of conventional approaches may not adequately capture carbon storage and sequestration in cactus systems, highlighting the need for adapted methodologies for biomass estimation and SOC assessment.

This review aims to identify the major land uses and cactus utilization systems that promote carbon storage and to provide a synthesis of methods for quantifying biomass, carbon stocks, and carbon sequestration in cactus-based ecosystems. Taking these considerations into account, the novelty of this review lies in providing a comprehensive methodological framework for assessing carbon sequestration in cactus-based ecosystems, thereby supporting more accurate and standardized carbon accounting across diverse dryland environments.

2. Methodology

We conducted a thorough literature search of peer-reviewed articles on cactus land use and the methods of estimating carbon stocks and/or C sequestration. First, we looked at cactus land use, including fruit orchards, intensive fodder systems, and their relative contribution to carbon sequestration. Various methods to quantify carbon stocks in cacti were explored, encompassing direct approaches like the destructive method, indirect methods such as allometric equations, remote sensing and machine learning, chronosequence, and use of the eddy covariance tower. We reviewed fine root input, mean residence time, and root turnover methods to estimate SOC dynamics. The literature search was conducted on Google Scholar, the Web of Science databases, and Scopus for articles published between 1995 and 2024 using the phrase carbon sequestration in cactus together with the following: orchards, rangelands, above and belowground biomass, SOC, chronosequence, remote sensing and machine learning, Eddy covariance tower, life cycle assessment, and carbon footprints.

3. Limitations of the study

This review is based on the currently available literature on carbon sequestration in cactus-based systems. The existing body of research is dominated by studies conducted in cultivated cactus plantations, whereas comparatively less information is available from natural and rangeland ecosystems where environmental heterogeneity, grazing, and management practices may influence carbon dynamics. In addition, studies have employed diverse methodologies, species, and measurement approaches, making direct comparisons among reported carbon sequestration estimates difficult. These factors highlight the need for greater standardization and

Table 1
Carbon sequestration potential and aboveground biomass productivity of cactus across regions and cultivation systems.

Country/Region	System	Condition	Species	Density of plantation (plants ha^{-1})	Biomass range (Mg DM ha^{-1} $year^{-1}$)	Estimated Carbon (t CO_2e ha^{-1} $year^{-1}$)[a]	Citation
Chile	Intensive fodder	Irrigated	*O. ficus-indica (L)*	240000	50	82.5	[13]
United States	Intensive fodder	Irrigation	*Opuntia spp.*	1418	7.8-14.7	12.9 - 24.3	[14]
Kenya	Intensive	Rainfed	*O. ficus-indica (L)*	20000	2.5- 8.2	4.1 - 13.5	[15]
United States	Intensive	Irrigated	*Opuntia spp.*	6667	1.5-13.3	2.5 - 22.0	[16]
Mexico	Intensive nopal production	Irrigated	O. ficus-indica cv. C-69	41,667	10.8-13.0[b]	17.8–21.4[b]	[17]
Brazil	Intensive fodder	Rainfed	*Opuntia spp.*	66,133	0.6 - 31.9	0.9–52.7	[18]
Brazil	Intensive fodder	Irrigated	*N. cochenillifera*	50000	8.6–34.7	14.2–57.3	[19]
Mediterranean Basin	Rangeland	Rainfed	*Opuntia spp.*	-	3–15	5.0–24.8	[20]

[a] Estimates of carbon equivalent were calculated according to Ho [21] using a coefficient of 0.45.
[b] Calculated from the reported fresh cladode yield of 108 t ha^{-1} yr^{-1}, assuming 10–12% dry matter content.

broader geographic coverage to improve understanding of the role of cactus-based systems in global carbon sequestration.

4. Land use and cactus utilization

4.1. Fruit orchards

Several studies have documented the potential of cacti to sequester carbon across different regions and land use systems (Table 1). For example, the ability of orchards to store carbon lies in their capacity to capture significant amounts of carbon in vegetative parts and retain it for an extended period [8]. Cactus orchards have the potential to sequester carbon due to the perennial nature of the crop. However, sequestering potential in orchards is influenced by several factors, including climate, soil type, crop and vegetation, and management practices [9]. Mature cactus can produce 9-10 fruits per square meter of cladode surface area, averaging 1.1-1.4 kg per square meter [10]. According to the author, cactus orchards can accumulate 7.5 tons of dry matter per hectare per year, with 3.4 tons stored in the canopy components, including fruits. According to Patil and Kumar [11], cactus species with greater fruit-bearing ability tend to increase carbon capture from the atmosphere and store it in cellulose. Although fruits and pruned cladodes would be in a fast-cycling pool and contribute little to carbon sequestration, the mother cladode and older cladodes could be significant carbon sinks due to their perennial nature. Notably, C storage in cactus orchards is influenced not only by biomass production but also by orchard age, as older Opuntia stands tend to accumulate greater amounts of soil organic carbon over time [12], highlighting the importance of stand development in long-term carbon sequestration.

For estimating carbon sequestration in cactus orchards, the relatively uniform planting arrangement and known plant population provide an opportunity for accurate biomass-based assessments. Information on planting density, orchard age, cultivar, and management practices such as pruning, fertilization, and irrigation can be combined with biomass measurements or allometric equations to estimate aboveground carbon stocks. In addition, repeated measurements and chronosequence can be used to quantify carbon accumulation rates and evaluate the long-term carbon sequestration potential of cactus orchards.

4.2. Fodder utilization in intensive orchards

Intensive cropping systems produce greater biomass, enhancing carbon sequestration [22]. According to Lima et al. [23], intensive systems for cactus fodder production, such as drip irrigation, can increase productivity in areas where warm night temperatures and lack of soil moisture limit cactus growth. Silva et al. [24] reported that productivity levels above 50 Mg DM ha^{-1} $year^{-1}$ could be achieved in intensive cultivation systems in rainfed semiarid agroecosystems, which include the use of high levels of manure (80 Mg ha^{-1} $year^{-1}$) and high plant population (160,000 plants per ha). In addition to increasing productivity, intensive agroforestry systems with forage cacti can enhance soil carbon stocks and aboveground carbon sequestration [5]. Although harvesting cladodes for forage removes organic matter from the aboveground biomass, the carbon in this organic matter can still be returned to the soil through various processes such as decomposition and nutrient cycling under grazing systems or manure applications. However, it is important to highlight that fodder utilization will result in livestock emitting greenhouse gases, mainly methane. Thus, the total balance of carbon inputs and outputs should be considered in intensive orchards for fodder utilization. Therefore, cacti used for fodder would contribute to carbon sequestration mostly from belowground tissues and SOC storage.

In addition, management practices in cacti under intensive systems have been reported to increase SOC. For example, Coêlho et al. [25] investigated how different management practices would affect SOC stocks in a field of cactus 'Orelha de Elefante Mexicana' (*Opuntia* spp.). The author tested 0, 10, 20, and 30 Mg cattle manure ha^{-1} yr^{-1} and observed a linear increase in SOC stocks. Higher levels of manure application led to SOC accumulation$>$ 120 Mg C ha^{-1} in the 0- to 20-cm layer. Therefore, proper orchard management can maximize carbon storage in cactus production systems.

4.3. Cactus in rangelands

Cactus-based systems offer significant potential to enhance carbon sequestration in dryland rangelands, where water scarcity often limits biomass production and carbon storage. The exceptional drought tolerance and high rain-use efficiency of *Opuntia* spp. enable sustained biomass accumulation under harsh environmental conditions, increasing carbon inputs to rangeland ecosystems [20]. Le Houérou [20] reported that establishing cactus in degraded arid and semi-arid rangelands can substantially increase vegetation cover and aboveground biomass, thereby enhancing carbon storage while reducing land degradation. Beyond biomass production, cactus contributes to carbon sequestration indirectly by improving soil protection, reducing erosion, enhancing water infiltration, and increasing soil organic matter accumulation [26]. These attributes make cactus an effective restoration species for degraded rangelands, where increasing plant productivity and stabilizing soils are critical for long-term carbon sequestration and ecosystem resilience under increasing climatic variability.

One major challenge in many rangelands in dry areas is overgrazing. Spiny cacti thrive in this region and may become invasive because their spines protect them from herbivory. Spiny cactus has been introduced to several countries worldwide during the colonial period and has become invasive in some regions [27]. Several strategies have been put in place to control the spread of cactus, including prescribed burning [28], herbicides [29], and biocontrol [30,31]. Another approach is adding value to the invasive cactus. After eliminating spines, the invasive cacti could be used for fodder, bioenergy, and other ecosystem services such as carbon sequestration, erosion control, and revegetation of degraded areas. However, this does not imply encouraging invasive plant species, but rather incorporating their use into current control efforts. Controlling grazing pressure and reducing stocking rates in degraded

rangelands could also restore endangered plant species and reduce the invasiveness of some cactus species.

Estimating carbon sequestration in cactus-dominated rangelands is more challenging than in orchards because of the heterogeneous distribution of plants, variable stand densities, mixed vegetation communities, and differences in grazing intensity and land management. In addition, the vast spatial extent and often remote nature of rangelands make direct biomass measurements labor-intensive and costly. Consequently, integration of multiple robust methods are needed to improve the accuracy of biomass and carbon stock assessments in these ecosystems.

5. Methods for biomass estimation in cactus fields

5.1. Direct measurements

The method involves the total harvest of the aboveground biomass in the study area and estimating the dry weight as described by Neupane et al. [14]. Plants are harvested to ground level, and the total fresh weight per unit area is recorded. Fresh weight of representative subsamples is then taken and dried at a constant temperature of 55°C until they reach a constant weight (pre-drying). These pre-dried samples can undergo further chemical analysis (e.g., nitrogen, carbon). Due to an abundance of epicuticular wax, the cladodes are cut open, and fruits are diced into small pieces to speed up dehydration. Finally, a subsample is dried at 105°C for 24 h, and the total dry weight is calculated as the ratio of the subsample's dry to fresh weight multiplied by the total fresh weight. A conversion factor of between 0.42 and 0.45 is used to convert biomass (dry weight) to carbon equivalents (ton) as proposed by Ho [21].

Direct biomass estimation has high accuracy but can be logistically costly because it is labor-intensive and time-consuming, and it involves storage, transport, and disposal challenges, especially when a large area needs to be sampled [32]. In addition, the method is ecologically sensitive and prevents future plant sampling, necessitating single-season studies or costly plot expansion for varied sampling periods. When sampling in rangeland, it is crucial to survey the stand and plant density per unit area to ensure that the sampling areas are representative of the study population. This can be achieved through aerial images and on-the-ground measurements, counting cactus clusters within specific areas [33,34]. Combining machine learning with remote sensing can enhance the ability to accurately quantify cactus stands at a large scale [33]. Performing a power analysis to determine the optimal sample size is crucial before initiating sampling, as it ensures the precision and reliability of the study results while optimizing resource utilization [35].

5.2. Allometric models

The Intergovernmental Panel on Climate Change (IPCC) provided new guidance to inventory compilers on using allometric models for quantifying biomass and carbon stocks in land uses containing vegetation [36]. Typically, allometric models are mathematical relationships between plant characteristics such as height, diameter, volume, leaf area, and plant biomass, which can then be converted into carbon estimates (Fig. 1). The goal is to develop predictive models that relate cladode dry weight to the biometric parameters and allow for non-destructive biomass estimation. In a study to estimate the aboveground biomass of *Opuntia ficus-indica*, Reis et al. [37] measured the biometric parameters of 60 cladodes aged between 1 and 2 years based on their length, width, mean thickness, and diameter of the junction between cladodes as shown in Fig. 1. The authors then used two methods, image analysis and the cladode weight paper silhouettes, to quantify the area of the cladodes. They developed a predictive model ($R^2 = 0.72$) that analyzed the relationship between the cladode area and the biometric parameters for non-destructive biomass estimation (equation (1)).

$$DW = 8.49 + 0.49\ (W \times T \times D) \tag{1}$$

Where DW - cladode dry weight (g), W - cladode maximum width (cm), T - cladode average thickness (cm), and D - diameter of the junction between cladodes (cm).

In a study to estimate the area and weight of forage cladodes, Lucena et al. [38] used linear dimensions. First, the authors randomly collected 432 cladodes from the study area, weighed and measured their length, width, and thickness. The regions of greatest length and width were used to determine the cladode area. The cladodes were then spread over millimeter graph paper, and their outlines were drawn and weighed to calculate the proportional cladode area. Regression analyses were performed using linear, gamma, and power models to determine the best-fit model for predicting the actual cladode area from the product of length and width. Eventually,

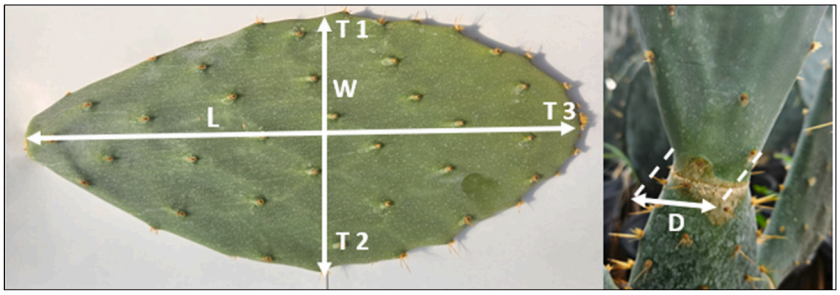

Fig. 1. Morphometry of cactus cladodes to determine biomass using an indirect method.

the best-fit model was used to predict cladode weight as a function of thickness and the product of length and width, using linear, gamma, and power models. Biomass was then estimated based on the weight of the cladodes.

Cladodes are typically arranged in a hierarchical branching pattern, with each successive order contributing differently to total biomass. Using this approach, Lopes et al. [39] estimated forage biomass in cactus by harvesting cladodes from three plants per plot (24 m^2) while preserving the primary cladodes for regrowth. The harvested cladodes were labeled and separated by order, and dried to constant weight for biomass estimation. Total forage production was calculated by adding the biomass from each cladode order, and harvestable forage biomass was calculated above the cutting height. Curt et al. [40] compared seasonal variation in the allometric method for biomass estimation and concluded that a single linear equation was sufficient for most of the growth cycle. Additional studies on the estimation of aboveground biomass in cactus using allometric models are summarized in Table 2.

According to IPCC [36], the validity of allometric models is contingent on factors such as individual growth conditions and size classes. Key considerations for model selection include ecoregion, geographic range, and environmental conditions. A thorough review of metadata associated with chosen models, including parameters like estimated plant components and species traits, is essential [44]. Ideally, if a single equation can accurately predict biomass for most of the growth cycle, it could simplify the estimation process and reduce the need for repeated measurements. However, this may only hold true when developing species- and site-specific allometric equations [45]. Similarly, other studies [46,47] have reported that applying allometric models beyond their developed range poses accuracy risks due to external variables that influence biomass partitioning and geometric relationships. To address this, rigorous testing of model applicability using representative datasets is recommended, with accuracy assessed using relevant statistical indicators. Although species-specific models offer precision [48,49], generalized models may be preferable in regions where specific models are unavailable for diverse species.

Stand-level models are used when individual or species-specific allometric models for biomass or carbon stocks are unavailable [36]. These models incorporate canopy height, basal area, and community age as predictor variables to estimate vegetation biomass. Canopy height in stand-level allometric models involves assessing carbon stocks per unit area, assuming a direct proportionality between canopy height and biomass [49,50]. Ground-based inventories or remote sensing techniques can provide canopy height information, which is crucial for accurate carbon stock estimation. The accuracy of carbon stock estimation depends on the number of field measurement plots used to establish the relationship between canopy height and carbon stocks.

According to Yuen et al. [51], the major drawback of allometric models is that their accuracy depends on the specific species, geographic range, and environmental conditions where they are developed, as variations in biomass partitioning and geometric relationships can affect their applicability. Growth factors, such as age and size classes, also influence model predictions, with potential errors arising during different growth stages or under stress conditions, such as drought [52]. Expanding datasets across ecosystems and species, along with rigorous validation, can improve the universality of biomass estimations. Standardizing metadata reporting on site conditions, methods, and validation criteria further facilitates broader applicability. Combining ground-based methods with remote sensing, such as LiDAR or satellite imagery, enhances scalability by providing precise data on parameters like canopy height and basal area. Establishing repositories of species-specific equations, particularly for underrepresented species such as cacti, is critical to improving precision and addressing gaps in global carbon estimation frameworks.

5.3. Remote sensing

Remote sensing involves using instruments and technology to gather information about an object, area, or phenomenon from a distance without direct contact [53]. Sensors, such as satellites or drones, gather data about the reflectance or emission of light from the Earth's surface [54]. The collected data is then processed with field-based measurements to estimate the aboveground biomass. One common approach to estimating cactus biomass using remotely sensed data is to use vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), which is a proxy for aboveground primary productivity [55]. Other vegetation indices, such as the Soil-Adjusted Vegetation Index (SAVI), have been used to estimate plant indicators in cactus fields [56]. This vegetation index is typically applied to minimize the effects of bare soil on vegetation reflectance [57]. Thus, SAVI could be an appropriate vegetation index for further investigation in cactus fields, as cacti typically grow in clusters, creating many bare-soil patches.

Distinguishing cacti from non-cacti plants in grazinglands is crucial for accurately estimating the proportion of aboveground biomass represented by cacti. Bates et al. [58] used a low-cost camera (RGB) coupled to a drone to detect and quantify Cactus (*Sclerocactus wrightiae* L.D. Benson) in desert grazinglands in the USA. Atitallah et al. [59] also demonstrated the potential of convolutional neural networks for cactus recognition based on drone imagery (Accuracy = 98%). Cacti can be distinguished from

Table 2
Additional studies on aboveground biomass estimation in cactus using allometric models.

Reference	Country	Cactus species	Equation	Input	Predictive Performance
[37]	Portugal	*Opuntia ficus-indica* (L.) Mill	$FW = 36.91 + 0.64\ (L \times W \times T)$	Length, Width, Thickness	$R^2 = 0.91$
[41]	Argentina	*Opuntia ficus-indica* (L.) Mill	$DW = 6.31 + 0.8\ (L \times W)$	Length, Width	$R^2 = 0.93$
[42]	Spain	*Opuntia dillenii*, *Opuntia maxima*	$DW = 1.5403 + BSD \times 0.3231$	Basal stem diameter	$R^2 = 0.42$
[13]	Chile	*Opuntia ficus-indica* (L.) Mill.	$TB = -10.0842 + BSD \times 4.112$	Basal stem diameter	$R^2 = 0.64$
			$DW = 88.3\ A + 2779\ A^2$	Cladode Surface area	$R^2 = 0.99$
[43]	United States	*Opuntia ficus-indica* (L) Mill.	DW = 0.477 x L x W x T	Width, Thickness	$R^2 = 0.93$
[38]	Brazil	*Nopalea cochenillifera*	WC = 0.536T + 0.028LW	Thickness, Length, Width	$R^2 = 0.99$

A = Surface area, BSD=Basal stem Diameter, FW=Fresh weight, DW = Dry weight, TB = Total biomass, SA= Surface area WC=Weight of cladode.

non-cacti plants by their unique spectral signatures, which are influenced by their morphological and anatomical characteristics [60]. Most cacti lack leaves and perform photosynthesis with the tissue layer of their stems. These structural differences affect how solar radiation is absorbed, which can be observed using hyperspectral imaging sensors [61].

Light Detection and Ranging (LiDAR) is an alternative technology that uses light to measure canopy height by estimating the distance between the sensor and the target vegetation [62]. In addition, digital elevation models derived from satellite or drone altimetric data have demonstrated the potential to estimate canopy height in crop and pasture lands by the difference between surface (i.e., vegetation) and ground elevations [63,64]. The same approach could be applied in cactus fields to estimate canopy height at lower cost than the LiDAR approach.

Regardless of the technology adopted, the first step is data acquisition, which involves obtaining remotely sensed data that covers the study area, such as satellite or drone imagery. These cost-effective and flexible tools provide fine spatial and temporal resolution data [65]. In a study to map *Opuntia stricta*, a combination of Sentinel-2 spectral bands, vegetation indices, and topographic indices achieved accuracies of 89.2% and 92.4% with the XGBoost and Random Forest (RF) classifiers, respectively [66]. Other satellite images can be explored based on the required resolution and the area's cloud cover. Drone images typically provide high-resolution data that can be used to validate and calibrate satellite images. Data pre-processing is the next step, including removing atmospheric effects, normalizing the data, and converting it to appropriate formats [66]. Next, analyze the spectral signature of cacti in the imagery to identify characteristic spectral bands or indices unique to cacti [67]. Other image features, such as color, texture, and elevation, can also be used to identify cacti plants and estimate different biophysical parameters. This is followed by biomass estimation, where the specified spectral bands, indices, and other image features are used to estimate biomass in cactus using empirical models, such as regression equations, that relate the spectral data to ground-based measurements of biomass or other parameters directly related to biomass, such as the area of a cladode [67]. Finally, the estimated biomass is validated using ground-based biomass measurements or other parameters.

Machine learning algorithms are generally used to analyze remotely sensed data and develop models that can predict biomass based on various input parameters [68]. Machine learning algorithms (e.g., ANN, XGBoost, and Random Forest) are powerful tools for identifying patterns in images and complex datasets and predicting various biophysical parameters in agricultural fields [69]. These models can be trained using ground truth data, which involves collecting field measurements of cactus biomass and comparing them with remotely sensed data. Artificial neural networks (ANNs) have been used to predict cacti biomass with high precision ($R^2 = 0.87$) [70]. The authors reported that total cladode area, plant height, cladode thickness, and cladode length contributed most to the total biomass estimates. Similarly, convolutional neural networks (CNN) have been highlighted for image classification and cactus detection purposes [59]. Generally, remote sensing technology can gather information about inaccessible or difficult-to-access areas and is a cost-effective way to acquire data over large areas at regular intervals [53].

However, the accuracy of remote sensing in estimating biomass and carbon stocks depends on proper calibration with ground-based measurements [71]]. Differentiating cacti from non-cacti plants in grazing lands requires precise spectral data, which is often hindered by environmental factors such as bare soil and overlapping vegetation reflectance [60]]. Advanced machine learning algorithms, including ANNs, have improved detection and biomass prediction accuracy but rely on high-quality ground-truth data and extensive datasets [53]]. Challenges such as the cost and availability of high-resolution imagery, especially in regions with frequent cloud cover, persist. Drone imagery offers higher spatial resolution but requires substantial data acquisition and processing resources. A lack of standardized data pre-processing and analysis methodologies contributes to inconsistent results. Standardizing protocols for image acquisition, spectral analysis, and biomass validation, alongside integrating remote sensing technologies with allometric models and metadata reporting, could significantly enhance accuracy and applicability on a global scale.

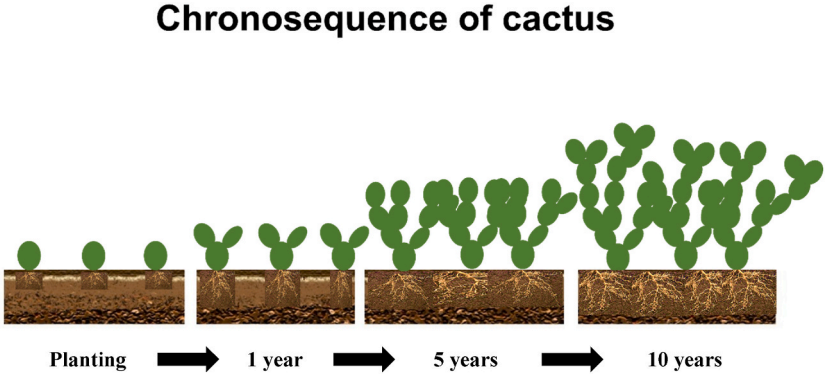

Fig. 2. A chronosequence of cactus indicating a series of sites with different ages found at a given time in a region under similar characteristics. A sampling of the series occurs at the same time, but orchards have different ages.

6. Estimating carbon sequestration in cactus systems

6.1. Chronosequences

A chronosequence is a series of sites with different ages since establishment and/or disturbance, occurring on similar soil types and under similar environmental conditions within the same climatic zone and historical land use. Sites are replicated in space as a substitute for replication in time, making this concept particularly valuable for assessing SOC sequestration under varying management or natural conditions. This method can be applied effectively to cactus orchards, where age differences across the sites are well documented. Under similar conditions but with a range of ages, a chronosequence allows researchers to evaluate the dynamics of SOC sequestration over time (Fig. 2). However, applying the chronosequence to rangeland cacti poses a challenge for determining age unless it is combined with modern remote sensing technology and image libraries. With the chronosequence identified, soil sampling should occur from the surface down to 1 m depth when possible, splitting into surface layers (0- to 15-, 15- to 30-cm depth) and deeper layers (30- to 60-, 60- to 100-cm depth). It is important to have the soil bulk density within each sampled layer and the SOC concentration. Some authors propose a correction for gravel and stone [72]. If the soil is rich in carbonates, it is important to determine organic and inorganic carbon following the procedure described by Harris et al. [73]. Once soil sampling is determined across the chronosequence sites, net carbon accumulation can be calculated by summing the SOC gains within the different age periods. This approach provides insights into the rate and extent of carbon sequestration over time during the different stages of cactus development.

6.2. Repeated measurements

Repeated measurements of soil over time, with the respective determination of SOC stock, is another potential methodology to assess soil carbon sequestration rate. The assumption is that the SOC (SOC) stock at a given time represents the net carbon accumulation (or loss) from the previous sampling. Processes such as carbon deposition and decay will occur during the time interval, but the net result will represent the sequestration rate during that interval. One drawback of this methodology is its limited sensitivity, especially over short-term intervals (<5 years). The short-term assessment might lack accuracy and precision because the SOM is the net result of long-term soil organic processes. One alternative approach is to fractionate the SOM into physical fractions associated with recent land-use changes. Physical fractions based on particle density, however, will not provide complete information regarding annual carbon sequestration rates of total organic carbon. Still, they can provide insight into whether a system is acting as a carbon sink or a carbon source to the atmosphere.

6.3. Eddy co-variance towers

Eddy covariance flux towers provide continuous measurements of the vertical concentration gradient of gases and, over time, integrate these measurements to calculate the flux of important gases such as CO_2 and CH_4 [74]. Typically, the carbon flux between the ecosystem and the atmosphere can be monitored (Fig. 3). It integrates photosynthesis and respiration over time to provide the net ecosystem carbon exchange [75]. Therefore, it is possible to determine the net carbon accumulation (or losses) of a cactus orchard using this system. One of the drawbacks is the cost of acquiring and maintaining the system, as well as the need for site replication to obtain more accurate measurements. A network of eddy covariance towers across different semiarid regions would be essential for long-term ecosystem measurements, including carbon sequestration rates. In a recent study, Jardim et al. [5] measured the carbon exchange in a cactus field in the semiarid region of Brazil using an Eddy covariance flux tower. They observed that cacti are potential

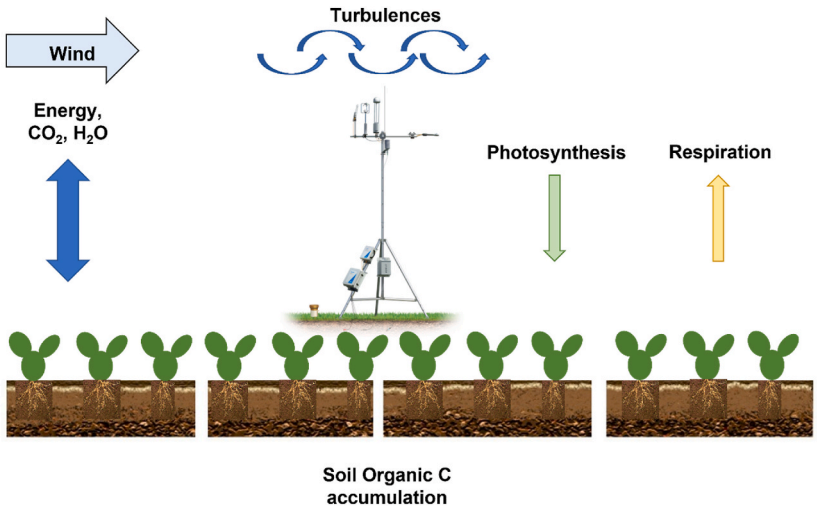

Fig. 3. Schematic design of an Eddy Covariance Flux Tower to measure carbon accumulation rates in cactus orchards.

year-round carbon sinks, with fluctuations in net carbon exchange rates depending on the seasons. Considering above and belowground carbon, the annual net C accumulation in the ecosystem was approximately 15 Mg C ha^{-1} yr^{-1}. Assuming that root biomass accounts for approximately 20% of total biomass [10], this corresponds to approximately 3 Mg C ha^{-1} yr^{-1} accumulated in roots. This is an extremely high rate of carbon sequestration below ground. If the aboveground carbon has a slower turnover, such as cactus trees for fruit production (instead of fodder for livestock), the belowground carbon accumulation would significantly mitigate the increase in atmospheric CO_2.

6.4. Fine root input, mean residence time, and root turnover

Annual root carbon input from cacti can be an indirect approach to assess carbon sequestration rates, and these rates can be estimated using a set of equations described by Novara et al. [72]. These authors estimated that the mean residence time (MRT) of cactus roots in Sicily, Italy, was approximately 10 years. They also found that MRT decreased with soil depth, highlighting the significance of deep root systems for carbon storage. If the field is a chronosequence after C3-predominant vegetation, stable isotopes can be an important tool for separating new carbon inputs from cacti from old carbon inputs from the C3 vegetation. Root turnover can also be estimated using the root in-growth cores and regular sampling intervals of the root biomass. For example, Hassan et al. [76] used the root turnover method to quantify the effects of soil volume on root growth and carbon turnover. The authors reported that roots in the smallest volume had a 36% higher carbon turnover rate than those in larger volumes, with turnover increasing by 10% for each decrease in soil volume. The hypothesis is that the root mass at a given time is the net result of root deposition minus root decay. Therefore, root decay turnover can be addressed by sampling root mass in subsequent periods and measuring root deposition with root-in-growth cores (Fig. 4).

Fine root input and root turnover are key indicators of carbon sequestration in *Opuntia* systems. Studies by Novara et al. [72] have shown that the annual carbon input from cactus roots is approximately 0.03 g C kg^{-1} soil. Root turnover rates decrease with soil depth, ranging from 7.1% per year in the topsoil (0–15 cm) to 3.7% in deeper layers (60–75 cm). Cactus roots' mean residence time (MRT) is estimated at 10 years, with slower turnover in deeper soil, enhancing long-term carbon storage. Methods such as stable isotope analysis can distinguish *Opuntia* root inputs from older vegetation, while root in-growth cores combined with periodic biomass sampling provide precise turnover measurements.

7. Soil carbon in cactus fields

More studies are needed to better understand and quantify SOC sequestration in cactus fields. Although there is information related to SOC stocks [78], the annual C sequestration rates are still missing. In the Mexican temperate subhumid region with high altitude

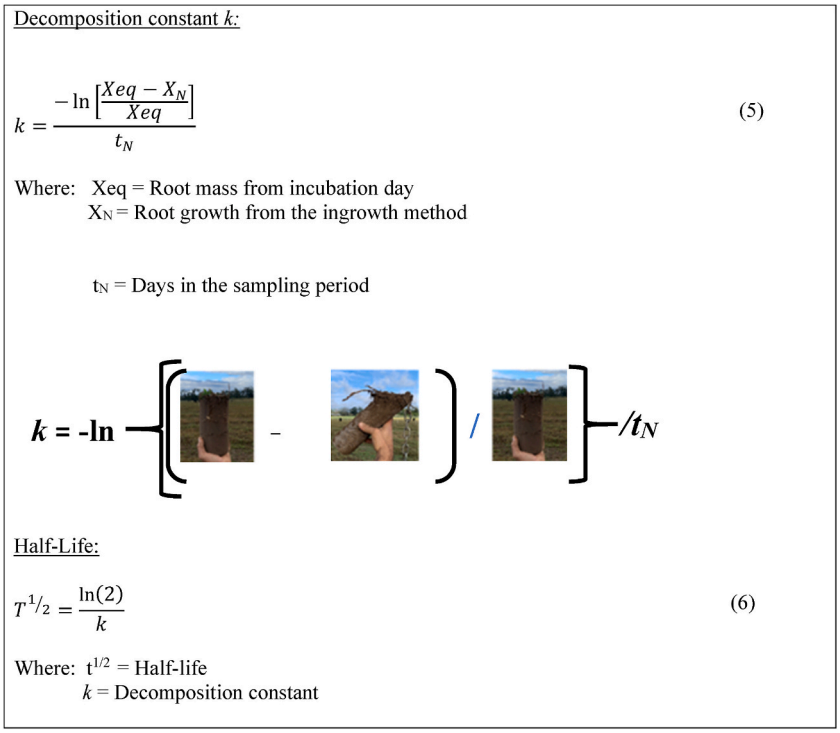

Fig. 4. Root decomposition constant and half-life measurements. Methods adapted from Ref. [77]. Credit to Dr. Erick R.S. Santos.

(2595 m asl), forest conversion to maize (*Zea mays* L.) resulted in losses of SOC; however, when the conversion occurred from forest to cactus, SOC content was maintained, increased carbon recalcitrance index, and improved soil extractable organic carbon content, which is related to increases in soil microbial biomass [79]. The authors concluded that cactus cropping systems improved soil quality after deforestation compared to the conversion from forest to maize and attribute this to high fine root turnover and root exudations, which are easily mineralizable [80]. In Sicily, Italy, the mean residence time of SOM under cactus systems was approximately ten years, and root turnover decreased with depth. Conversion from native vegetation (Mediterranean Maquis) with deep plowing to cactus orchards resulted in a net loss of soil organic matter. Disturbances in land cover, especially when using deep plowing, commonly lead to losses of SOM, followed by a stabilization period, and then a new steady state that can be at a lower level, similar, or greater than the previous SOM levels, depending on the new management [81]. In a recent publication [78], observed that SOC stock under a well-managed cactus orchard in Brazil reached almost 100 Mg C ha^{-1} in the 0- to 20-cm soil layer, indicating the potential of cactus to store carbon. The soil in this site is classified as Regolitic Neosol, which does not have a well-developed profile (shallow). In this example, adding organic amendment (cattle manure) over the previous ten years of management likely helped the cactus increase its net primary productivity and store organic carbon in the soil.

In dryland regions, soil inorganic carbon (SIC) has received increased attention recently. Storage of SIC is a complex mechanism involving multiple interactions of several factors such as climate, land use types, farm management practices, irrigation, soil properties, and soil biotic factors, among others [82]. The soil inorganic carbon formation resulting from biological activities is called pedogenic inorganic carbon (PIC). Not all arid regions are favorable for pedogenic carbonate formation, and four conditions are essential: 1. High soil pH (alkaline); 2. An active source of CO_2 in the soil for HCO_3^- production; 3. A large amount of available Ca^{2+}; and 4. An optimum level of soil moisture. In arid regions, SIC, especially calcium (and magnesium) carbonates, are formed via the following two reactions:

$$2CO_2 + 2H_2O \text{ ---------- } 2HCO_3^- + 2H^+ \quad (2)$$

$$Ca^{2+} + 2HCO_3^- \text{ ---------- } CaCO_3 + H_2O + CO_2 \quad (3)$$

Depending on the conditions, these reactions can go to the right or left. High soil pH will result in HCO_3^- formation, with equation (3) proceeding to the right. Likewise, a decrease in soil pH or increased soil CO_2 would cause equation (3) to shift to the left. The soil CO_2 comes from plant roots and microbial respiration. A shift in SOC stock indicates a shift in carbon sequestration; however, this is not true for SIC [82]. Three SIC processes affect the soil-atmosphere exchange of CO_2, including silicate mineral weathering, carbonate dissolution, and pedogenic inorganic carbon formation. In recent years, claims have emerged that cacti can play a significant role in sequestering SIC. The assumption is based on the fact that cacti typically have high calcium concentrations in their biomass. Once calcium is deposited back into the soil and combined with soil CO_2 from root respiration, it could lead to SIC formation. However, the major flaw in this assumption is that the calcium in the cactus tissue was taken up from the soil as a product of carbonate dissolution, as indicated in Equation (3). During this process, CO2 is released, with no net carbon gain [83]. Unless new calcium is added to the system, there will be no net carbon gain. Adding calcium via lime might also increase the system's carbon footprint if the life cycle assessment (LCA) is considered for lime manufacturing, transportation, and application. Therefore, the formation of SIC does not appear to be a major mechanism for increasing carbon sequestration in cactus fields, with SOC remaining the primary mechanism.

8. Cactus biochar

The biomass potential of cacti makes them ideal feedstocks for biochar production, which can enhance soil carbon sequestration. Studies by Maaoui et al. [84] demonstrated the successful conversion of *Opuntia ficus-indica* biomass into biochar through pyrolysis, highlighting the potential of cactus-derived biochar as a sustainable strategy for carbon storage and biomass valorization in dryland environments. More recently, Maaoui et al. [85] reported that biochar produced from cactus cladodes exhibited high porosity, abundant functional groups, and substantial calcium content, characteristics that can enhance nutrient retention, soil quality, and long-term carbon stabilization.

Despite this opportunity, the use of biochar derived from cactus to enhance carbon sequestration remains underexplored. Research is needed to optimize pyrolysis to maximize biochar using cactus feedstock. The dynamics, including the rate and extent of carbon sequestration using cactus-based biochar, also need to be studied. This requires long-term studies, which are currently lacking. Another area that requires exploration is the conversion of biomass from invasive cactus species, such as *Opuntia stricta* Haw., into biochar. This approach could help address the ecological threat posed by this invasive species to rangeland ecosystems while reducing carbon emissions. In cactus orchards, pruning residues and fruit peels could be repurposed for biochar production, adding value to these by-products.

9. Policy frameworks for cactus-based carbon offset programs

Despite the well-documented carbon sequestration potential of cacti, a significant gap remains in developing policy frameworks to support cactus-based carbon offset programs. Public policies and credit mechanisms are crucial for promoting cactus cultivation in arid and semi-arid regions worldwide. For example, in Mexico, *Opuntia* is used in agroforestry systems designed to enhance soil carbon stocks and rural livelihoods, aligning with the country's Paris Agreement goals [86]. Brazil incorporates *Opuntia* into semi-arid areas such as the Caatinga biome, promoting agroforestry to boost carbon stocks and support sustainable development [87]. South Africa's initiatives promote cactus plantations to combat land degradation and explore *Opuntia* as a livestock feed and bioenergy source,

contributing to carbon offset benefits [88].

In countries such as Kenya, Ethiopia, and Madagascar, where invasive cactus species pose a problem [89], policies are needed to repurpose these plants. Finding practical uses, such as livestock feed, bioenergy, or soil improvement, while gradually replacing invasive species with cultivated varieties could address ecological concerns and contribute to carbon offset programs. However, policy frameworks are required to guide sustainable management practices, incentivize research, and integrate cactus cultivation into national climate adaptation and mitigation strategies. To facilitate cactus-based carbon offset programs, governments should develop carbon accounting and verification protocols that quantify carbon stored in cactus biomass and soils. In addition, incentive mechanisms such as carbon credits, payments for ecosystem services, and support for cactus-based bioenergy, livestock feed, and biofertilizer industries could encourage adoption while generating economic benefits for dryland communities.

10. Future research directions

Future research should expand beyond cultivated cactus plantations and evaluate carbon sequestration in natural and managed rangelands, where greater variability in climate, soils, grazing pressure, and vegetation composition may influence carbon dynamics. Long-term studies are needed to quantify changes in biomass carbon, soil organic carbon, and belowground carbon pools across different ecosystems and management regimes. In addition to carbon storage, future work should assess broader ecosystem services provided by cactus-dominated systems, including biodiversity conservation, soil stabilization, drought resilience, forage production, and climate adaptation benefits. The integration of advanced technologies, such as remote sensing, unmanned aerial vehicles (UAVs), machine learning, and geospatial modeling, could improve the estimation and monitoring of carbon stocks across large, difficult-to-access dryland landscapes. Finally, standardized methodologies for measuring, reporting, and verifying carbon sequestration are required to support the inclusion of cactus-based systems in carbon markets and climate mitigation programs.

11. Conclusion

Dryland agriculture will be increasingly important in providing ecosystem services to future generations, and cactus (*Opuntia* spp.) is a significant crop for these areas. Cactus can provide food, fodder, energy, other products, and other ecosystem services, including soil carbon sequestration. There are multiple ways to assess carbon sequestration in cactus fields, but more research is needed on this topic. Aboveground carbon in cactus orchards may be considered a potential carbon sink, depending on the use of the biomass and its potential to turn carbon back into the atmosphere. Cactus growing in rangelands with less intensive cultivation or cactus orchards for fruit production, when trees can live for an extended period, could be a potential sink for aboveground carbon. However, belowground carbon is the primary mechanism of carbon sequestration to offset GHG emissions. Soil organic carbon is more recalcitrant than aboveground biomass, taking longer to turn over. Despite this potential, there are significant gaps in quantifying belowground carbon in cacti, and a need for long-term studies to quantify carbon sequestration rates. This review examined the areas covered by cacti and identified potential methods to quantify their carbon sequestration. Future research is needed to validate these methods and assess cacti's potential to sequester carbon across a range of environmental conditions and management practices.

CRediT authorship contribution statement

Kenneth T. Oduor: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jose C.B. Dubeux:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Igor L. Bretas:** Writing – review & editing, Writing – original draft, Conceptualization. **Luana M.D. Queiroz:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors sincerely thank dryGrow Foundation (Project number P0190221) for supporting the publication of this work.

Data availability

No data was used for the research described in the article.

References

[1] L. Wang, W. Jiao, N. MacBean, M.C. Rulli, S. Manzoni, G. Vico, P. D'Odorico, Dryland productivity under a changing climate, Nat. Clim. Change 12 (2022) 981–994, https://doi.org/10.1038/s41558-022-01499-y.

[2] M.S. Arshad, M. Sanaullah, M. Farooq, Soil carbon sequestration in dryland agriculture, in: M. Farooq, K.H.M. Siddique (Eds.), Innov. Dryland Agric., Springer International Publishing, Cham, 2016, pp. 469–490, https://doi.org/10.1007/978-3-319-47928-6_17.

[3] R. Lal, Carbon cycling in global drylands, Curr. Clim. Change Rep. 5 (2019) 221–232, https://doi.org/10.1007/s40641-019-00132-z.

[4] D. Khan, A. Harris, Q.U. Zaman, H. Wang, J. Wen, J.B. Landis, H. Wang, The evolutionary history and distribution of cactus germplasm resources, as well as potential domestication under a changing climate, J. Syst. Evol. (2024), https://doi.org/10.1111/jse.13042 jse.13042.

[5] A.M. da R.F. Jardim, J.E.F. de Morais, L.S.B. de Souza, F.R. Marin, M.S.B. de Moura, L.P.C. Morellato, A.A. de A. Montenegro, J.P.H.B. Ometto, J.L.M.P. de Lima, J.C.B. Dubeux Júnior, T.G.F. da Silva, Sink or carbon source? How the Opuntia cactus agroecosystem interacts in the use of carbon, nutrients and radiation in the Brazilian semi-arid region, J. Hydrol. 625 (2023) 130121, https://doi.org/10.1016/j.jhydrol.2023.130121.

[6] M. Khodaeiaminjan, A.A. Nassrallah, K.Y. Kamal, Potential attribute of Crassulacean acid metabolism of Opuntia spp. production in water-limited conditions, in: M.F. Ramadan, T.E.M. Ayoub, S. Rohn (Eds.), Opuntia Spp Chem. Bioactivity Ind. Appl., Springer International Publishing, Cham, 2021, pp. 201–218, https://doi.org/10.1007/978-3-030-78444-7_9.

[7] A.O.S. Jorge, A.S.G. Costa, M.B.P.P. Oliveira, Adapting to climate change with Opuntia, Plants 12 (2023) 2907, https://doi.org/10.3390/plants12162907.

[8] S. Sharma, V.S. Rana, H. Prasad, J. Lakra, U. Sharma, Appraisal of carbon capture, storage, and utilization through fruit crops, Front. Environ. Sci. 9 (2021), https://doi.org/10.3389/fenvs.2021.700768.

[9] R.S. Meena, S. Kumar, G.S. Yadav, Soil carbon sequestration in crop production, in: R.S. Meena (Ed.), Nutr. Dyn. Sustain. Crop Prod., Springer Singapore, Singapore, 2020, pp. 1–39, https://doi.org/10.1007/978-981-13-8660-2_1.

[10] P. Inglese, G. Gugliuzza, G. Liguori, Fruit production of cultivated cacti: a short overview on plant ecophysiology and C budget. https://doi.org/10.17660/ActaHortic.2009.811.6, 2009. (Accessed 18 March 2023).

[11] P. Patil, A.K. Kumar, Biological Carbon Sequestration Through Fruit Crops (Perennial crops-natural "Sponges" for Absorbing Carbon Dioxide from Atmosphere), 2017.

[12] G. Greco, G. Liguori, F. Gargano, P. Inglese, C. Souza De Sousa, M. Ruiz Moreno, J.C.B. Dubeux, *Opuntia ficus-indica* chronosequence affects soil carbon mineralization rates, Acta Hortic. (2026) 53–62, https://doi.org/10.17660/ActaHortic.2026.1452.7.

[13] V.G. de Cortázar, P.S. Nobel, Biomass and fruit production for the prickly pear cactus, Opuntia ficus-indica, J. Am. Soc. Hortic. Sci. 117 (1992) 558–562, https://doi.org/10.21273/JASHS.117.4.558.

[14] D. Neupane, J.A. Mayer, N.A. Niechayev, C.D. Bishop, J.C. Cushman, Five-year field trial of the biomass productivity and water input response of cactus pear (Opuntia spp.) as a bioenergy feedstock for arid lands, GCB Bioenergy 13 (2021) 719–741, https://doi.org/10.1111/gcbb.12805.

[15] J. Krümpel, T. George, B. Gasston, G. Francis, A. Lemmer, Suitability of Opuntia ficus-indica (L) Mill. and Euphorbia tirucalli L. as energy crops for anaerobic digestion, J. Arid Environ. 174 (2020) 104047, https://doi.org/10.1016/j.jaridenv.2019.104047.

[16] D. Neupane, N.A. Niechayev, L.M. Petrusa, C. Heinitz, J.C. Cushman, Biomass production of 14 accessions of cactus pear (*Opuntia* spp.) under semi-arid land conditions, J. Agron. Crop Sci. 210 (2024) e12705, https://doi.org/10.1111/jac.12705.

[17] A. Flores-Hernández, I. Orona-Castillo, B. Murillo-Amador, J.L. Garcia-Hernandez, E. Troyo-Dieguez, Yield and physiological traits of prickly pear cactus 'nopal' (Opuntia spp.) cultivars under drip irrigation, Agric. Water Manag. 70 (2004) 97–107, https://doi.org/10.1016/j.agwat.2004.06.002.

[18] R.L. Edvan, R.R.M. Mota, T.P. Dias-Silva, R.R. Do Nascimento, S.V. De Sousa, A.L. Da Silva, M.J.D. Araújo, J.S. Araújo, Resilience of cactus pear genotypes in a tropical semi-arid region subject to climatic cultivation restriction, Sci. Rep. 10 (2020) 10040, https://doi.org/10.1038/s41598-020-66972-0.

[19] G.F.D.C. Lima, M.M.T. Rego, F.D.G. Dantas, R.N.B. Lôbo, J.G.M.D. Silva, E.M.D. Aguiar, Morphological characteristics and forage productivity of irrigated cactus pear under different cutting intensities, Rev. Caatinga 29 (2016) 481–488, https://doi.org/10.1590/1983-21252016v29n226rc.

[20] H.N. Le Houérou, The role of cacti (Opuntiaspp.) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin, J. Arid Environ. 33 (1996) 135–159, https://doi.org/10.1006/jare.1996.0053.

[21] L.C. Ho, Variation in the carbon/dry matter ratio in plant material, Ann. Bot. 40 (1976) 163–165, https://doi.org/10.1093/oxfordjournals.aob.a085109.

[22] S. Machado, K. Rhinhart, S. Petrie, Long-term cropping system effects on carbon sequestration in Eastern Oregon, J. Environ. Qual. 35 (2006) 1548–1553, https://doi.org/10.2134/jeq2005.0201.

[23] G.F.C. Lima, M.M.T. Rêgo, E.M. Aguiar, B.J.G.M. Silva, F.D.G. Dantas, F.X. Guedes, R.N.B. Lôbo, B. Brazil, Effect of different cutting intensities on morphological characteristics and productivity of irrigated nopalea forage cactus. https://doi.org/10.17660/ActaHortic.2015.1067.35, 2015.

[24] G. dos S. Silva, R.A. de Oliveira, N.L. Queiroz, M.N.B. da Silva, M.F. de Sousa, S.A. da Silva, Agronomic performance of organic cotton and oilseed crops in combination with forage palm, Rev. Bras. Eng. Agrícola Ambient. 17 (2013) 975–981, https://doi.org/10.1590/S1415-43662013000900010.

[25] D.D.L. Coêlho, J.C.B. Dubeux, M.V.F.D. Santos, A.C.L.D. Mello, M.V.D. Cunha, D.C.D. Santos, E.V.D. Freitas, E.R.D.S. Santos, N.V.D. Silva, Management practices affect soil organic carbon stocks and soil fertility in cactus orchards, Agronomy 13 (2023) 2986, https://doi.org/10.3390/agronomy13122986.

[26] A. Nefzaoui, H.B. Salem, Cacti: efficient tool for rangeland rehabilitation, in: Drought Mitigation and to Combat Desertification, 2002, https://doi.org/10.17660/ActaHortic.2002.581.35.

[27] A. Novoa, J.J. Le Roux, M.P. Robertson, J.R.U. Wilson, D.M. Richardson, Introduced and invasive cactus species: a global review, AoB Plants 7 (2015) 1–14, https://doi.org/10.1093/aobpla/plu078.

[28] S.C. Bunting, H.A. Wright, L.F. Neuenschwander, Long-term effects of fire on cactus in the Southern mixed prairie of Texas, J. Range Manag. 33 (1980) 85, https://doi.org/10.2307/3898415.

[29] J.L. Petersen, D.N. Ueckert, R.L. Potter, Herbicidal control of pricklypear cactus in Western Texas, J. Range Manag. 41 (1988) 313, https://doi.org/10.2307/3899386.

[30] J.H. Hoffmann, V.C. Moran, H.G. Zimmermann, F.A.C. Impson, Biocontrol of a prickly pear cactus in South Africa: reinterpreting the analogous, renowned case in Australia, J. Appl. Ecol. 57 (2020) 2475–2484, https://doi.org/10.1111/1365-2664.13737.

[31] N. Venter, B.W. Cowie, M.J. Byrne, Prospects for the biological control of the invasive cactus, Opuntia stricta using Dactylopius opuntiae, under conditions of rising atmospheric CO2, Biol. Control 176 (2022) 105095, https://doi.org/10.1016/j.biocontrol.2022.105095.

[32] T. Maia Araújo, N. Higuchi, J. Andrade de Carvalho Júnior, Comparison of formulae for biomass content determination in a tropical rain forest site in the state of Pará, Brazil, For. Ecol. Manag. 117 (1999) 43–52, https://doi.org/10.1016/S0378-1127(98)00470-8.

[33] M. Rigge, C. Homer, L. Cleeves, D.K. Meyer, B. Bunde, H. Shi, G. Xian, S. Schell, M. Bobo, Quantifying Western U.S. rangelands as fractional components with multi-resolution remote sensing and in situ data, Remote Sens. 12 (2020) 412, https://doi.org/10.3390/rs12030412.

[34] P.P. Krening, C.A. Dawson, K.W. Holsinger, J.W. Willoughby, A sampling-based approach to estimating the minimum population size of the federally threatened Colorado hookless cactus (Sclerocactus glaucus), Nat. Area J. 41 (2021) 4–10, https://doi.org/10.3375/043.041.0102.

[35] A.S. Singh, M.B. Masuku, Sampling techniques & determination of sample size in applied statistics research: an overview, Int. J. Econ. Commer. Manag. 2 (2014) 1–22.

[36] IPCC, Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 4 (2019). Agriculture, Forestry and Other Land Use, 2019.

[37] C.M.G. Reis, L.C. Gazarini, T.F. Fonseca, M.M. Ribeiro, Above-ground biomass estimation of Opuntia ficus-indica (L.) Mill. for forage crop in a Mediterranean environment by using non-destructive methods, Exp. Agric. 54 (2018) 227–242, https://doi.org/10.1017/S0014479716000211.

[38] L.R.R. de Lucena, M.L. de, M.V. Leite, V.J.L.P. Simões, C. Nóbrega, M.C.R. Almeida, J.B. Simplício, Estimating the area and weight of cactus forage cladodes using linear dimensions, Acta Sci. Agron. 43 (2020) e45460, https://doi.org/10.4025/actasciagron.v43i1.45460.

[39] M.N. Lopes, M.J.D. Cândido, G.M.F. Gomes, T.D. Maranhão, E. da Costa Gomes, I. Soares, R.C.F.F. Pompeu, R.G. da Silva, Forage biomass and water storage of cactus pear under different managements in semi-arid conditions, Rev. Bras. Zootec. 50 (2021) 1–17, https://doi.org/10.37496/RBZ5020210022.

[40] M.D. Curt, F. Sánchez, J. Sánchez, P.L. Aguado, M. Uceda, G. Zaragoza, J.M. Agüera, J. Fernández, Allometric Method for the Estimation of Prickly Pear (Opuntia ficus-indica (L.) Miller) Biomass Weight: Comparison Between Seasonal Data, 2011.

[41] S. Caloggero, C.A. Parera, Assessment of prickly pear (Opuntia ficus-indica) varieties and their possible planting systems, Spanish J. Agric. Res. 2 (2004) 401, https://doi.org/10.5424/sjar/2004023-95.

[42] E.R. Pérez, Calculation of Carbon Storage of Invasive Species (Opuntia spp.) in Tenerife, 2022.

[43] Y. Luo, P.S. Nobel, Growth characteristics of newly initiated cladodes of *Opuntia ficusindica* as affected by shading, drought and elevated CO $_2$, Physiol. Plantarum 87 (1993) 467–474, https://doi.org/10.1111/j.1399-3054.1993.tb02495.x.

[44] G. Vieilledent, R. Vaudry, S.F.D. Andriamanohisoa, O.S. Rakotonarivo, H.Z. Randrianasolo, H.N. Razafindrabe, C.B. Rakotoarivony, J. Ebeling, M. Rasamoelina, A universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models, Ecol. Appl. 22 (2012) 572–583, https://doi.org/10.1890/11-0039.1.

[45] B. Kebede, T. Soromessa, Allometric equations for aboveground biomass estimation of Olea europaea L. subsp. cuspidata in Mana Angetu Forest, Ecosyst. Health Sustain 4 (2018) 1–12, https://doi.org/10.1080/20964129.2018.1433951.

[46] W.A. Mugasha, E.E. Mwakalukwa, E. Luoga, R.E. Malimbwi, E. Zahabu, D.S. Silayo, G. Sola, P. Crete, M. Henry, A. Kashindye, Allometric models for estimating tree volume and aboveground biomass in lowland forests of Tanzania, Int. J. For. Res. 2016 (2016) 1–13, https://doi.org/10.1155/2016/8076271.

[47] V.T. Nam, M. van Kuijk, N.P.R. Anten, Allometric equations for aboveground and belowground biomass estimations in an evergreen Forest in Vietnam, PLoS One 11 (2016) e0156827, https://doi.org/10.1371/journal.pone.0156827.

[48] M. Henry, N. Picard, C. Trotta, R. Manlay, R. Valentini, M. Bernoux, L. Saint-André, Estimating tree biomass of sub-saharan African forests: a review of available allometric equations, Silva Fenn. 45 (2011), https://doi.org/10.14214/sf.38.

[49] J. Mascaro, G.P. Asner, H.C. Muller-Landau, M. van Breugel, J. Hall, K. Dahlin, Controls over aboveground forest carbon density on Barro Colorado Island, Panama, Biogeosciences 8 (2011) 1615–1629, https://doi.org/10.5194/bg-8-1615-2011.

[50] S.S. Saatchi, N.L. Harris, S. Brown, M. Lefsky, E.T.A. Mitchard, W. Salas, B.R. Zutta, W. Buermann, S.L. Lewis, S. Hagen, S. Petrova, L. White, M. Silman, A. Morel, Benchmark map of forest carbon stocks in tropical regions across three continents, Proc. Natl. Acad. Sci. 108 (2011) 9899–9904, https://doi.org/10.1073/pnas.1019576108.

[51] J.Q. Yuen, T. Fung, A.D. Ziegler, Review of allometric equations for major land covers in SE Asia: uncertainty and implications for above- and below-ground carbon estimates, For. Ecol. Manag. 360 (2016) 323–340, https://doi.org/10.1016/j.foreco.2015.09.016.

[52] C. Pélabon, C. Firmat, G.H. Bolstad, K.L. Voje, D. Houle, J. Cassara, A.L. Rouzic, T.F. Hansen, Evolution of morphological allometry, Ann. N. Y. Acad. Sci. 1320 (2014) 58–75, https://doi.org/10.1111/nyas.12470.

[53] K.T. Vashum, Methods to estimate above-ground biomass and carbon stock in natural forests - a review, J. Ecosyst. Ecography 2 (2012), https://doi.org/10.4172/2157-7625.1000116.

[54] M.A. Ashraf, MohdJ. Maah, I. Yusoff, Introduction to remote sensing of biomass, in: I. Atazadeh (Ed.), Biomass Remote Sens. Biomass, 2011, https://doi.org/10.5772/16462. IntechOpen, Rijeka.

[55] E.H. Estrella, A. Stoeth, N.Y. Krakauer, N. Devineni, Quantifying vegetation response to environmental changes on the Galapagos Islands, Ecuador using the normalized difference vegetation index (NDVI), Environ. Res. Commun. 3 (2021) 065003, https://doi.org/10.1088/2515-7620/ac0bd1.

[56] A.A. Muharram, E. Tola, R.S. Al-Obeed, F. Al-Qurainy, K.A. Al-Gaadi, R. Madugundu, A.M. Zeyada, M.K. Edrris, N. Mohammed, A.A. Aldubai, Using spectral vegetation indices to study the growth of Opuntia ficus-indica and identify suitable production sites in the Southwestern region of Saudi Arabia, Pertanika J. Trop. Agric. Sci. 49 (2026), https://doi.org/10.47836/pjtas.49.2.08.

[57] A.R. Huete, A soil-adjusted vegetation index (SAVI), Remote Sens. Environ. 25 (1988) 295–309, https://doi.org/10.1016/0034-4257(88)90106-X.

[58] T.H. Bates, V.J. Anderson, R.L. Johnson, L. Allphin, D. Rooks, S.L. Petersen, A practical assessment of using sUASs (Drones) to detect and quantify wright fishhook cactus (Sclerocactus wrightiae L.D. benson) populations in desert grazinglands, Land 11 (2022) 655, https://doi.org/10.3390/land11050655.

[59] S.B. Atitallah, M. Driss, W. Boulila, A. Koubaa, N. Atitallah, H.B. Ghézala, An enhanced randomly initialized convolutional neural network for columnar cactus recognition in unmanned aerial vehicle imagery, Procedia Comput. Sci. 192 (2021) 573–581, https://doi.org/10.1016/j.procs.2021.08.059.

[60] K. Hartfield, J.K. Gillan, C.L. Norton, C. Conley, W.J.D. van Leeuwen, A novel spectral index to identify cacti in the sonoran desert at multiple scales using multi-sensor hyperspectral data acquisitions, Land 11 (2022), https://doi.org/10.3390/land11060786.

[61] R.F. Kokaly, R.N. Clark, G.A. Swayze, K.E. Livo, T.M. Hoefen, N.C. Pearson, R.A. Wise, W. Benzel, H. Lowers, R.L. Driscoll, Usgs Spectral Library Version 7 Data: Us Geological Survey Data Release, U. S. Geol. Surv. USGS Rest, VA USA, 2017, https://doi.org/10.3133/ds1035.

[62] J. Sankey, S. Munson, R. Webb, C. Wallace, C. Duran, Remote sensing of sonoran desert vegetation structure and phenology with ground-based LiDAR, Remote Sens. 7 (2014) 342–359, https://doi.org/10.3390/rs70100342.

[63] J. Batistoti, J. Marcato Junior, L. Ítavo, E. Matsubara, E. Gomes, B. Oliveira, M. Souza, H. Siqueira, G. Salgado Filho, T. Akiyama, W. Gonçalves, V. Liesenberg, J. Li, A. Dias, Estimating pasture biomass and canopy height in Brazilian savanna using UAV photogrammetry, Remote Sens. 11 (2019) 2447, https://doi.org/10.3390/rs11202447.

[64] L. Malambo, S.C. Popescu, S.C. Murray, E. Putman, N.A. Pugh, D.W. Horne, G. Richardson, R. Sheridan, W.L. Rooney, R. Avant, M. Vidrine, B. McCutchen, D. Baltensperger, M. Bishop, Multitemporal field-based plant height estimation using 3D point clouds generated from small unmanned aerial systems high-resolution imagery, Int. J. Appl. Earth Obs. Geoinformation 64 (2018) 31–42, https://doi.org/10.1016/j.jag.2017.08.014.

[65] S. Sun, N. Liang, Z. Zuo, D. Parsons, J. Morel, J. Shi, Z. Wang, L. Luo, L. Zhao, H. Fang, Y. He, Z. Zhou, Estimation of botanical composition in mixed clover–grass fields using machine learning-based image analysis, Front. Plant Sci. 12 (2021) 1–12, https://doi.org/10.3389/fpls.2021.622429.

[66] J.M. Muthoka, E.E. Salakpi, E. Ouko, Z.F. Yi, A.S. Antonarakis, P. Rowhani, Article mapping Opuntia stricta in the arid and semi-arid environment of Kenya using sentinel-2 imagery and ensemble machine learning classifiers, Remote Sens. 13 (2021) 1–21, https://doi.org/10.3390/rs13081494.

[67] X.A. Jaime, J.P. Angerer, C. Yang, J. Walker, J. Mata, D.R. Tolleson, X.B. Wu, Exploring effective detection and spatial pattern of prickly pear cactus (Opuntia genus) from airborne imagery before and after prescribed fires in the Edwards Plateau, Remote Sens. 15 (2023) 4033, https://doi.org/10.3390/rs15164033.

[68] Y. Zhang, J. Ma, S. Liang, X. Li, M. Li, An evaluation of eight machine learning regression algorithms for forest aboveground biomass estimation from multiple satellite data products, Remote Sens. 12 (2020) 1–26, https://doi.org/10.3390/rs12244015.

[69] I. Ali, F. Greifeneder, J. Stamenkovic, M. Neumann, C. Notarnicola, Review of machine learning approaches for biomass and soil moisture retrievals from remote sensing data, Remote Sens. 7 (2015) 16398–16421, https://doi.org/10.3390/rs71215841.

[70] B.V.C. Guimarães, S.L.R. Donato, A.M. Azevedo, I. Aspiazú, A.A. e Silva Junior, Prediction of 'Gigante' cactus pear yield by morphological characters and artificial neural networks, Rev. Bras. Eng. Agrícola Ambient. 22 (2018) 315–319, https://doi.org/10.1590/1807-1929/agriambi.v22n5p315-319.

[71] L. Mao, M. Li, W. Shen, Remote sensing applications for monitoring terrestrial protected areas: progress in the last decade, Sustainability 12 (2020) 5016, https://doi.org/10.3390/su12125016.

[72] A. Novara, P. Pereira, A. Santoro, Y. Kuzyakov, T. La Mantia, Effect of cactus pear cultivation after Mediterranean maquis on soil carbon stock, δ13C spatial distribution and root turnover, Catena 118 (2014) 84–90, https://doi.org/10.1016/j.catena.2014.02.002.

[73] D. Harris, W.R. Horwáth, C. Van Kessel, Acid fumigation of soils to remove carbonates prior to total organic carbon or CARBON-13 isotopic analysis, Soil Sci. Soc. Am. J. 65 (2001) 1853–1856, https://doi.org/10.2136/sssaj2001.1853.

[74] M.L. Goulden, J.W. Munger, S. Fan, B.C. Daube, S.C. Wofsy, Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy, Glob. Change Biol. 2 (1996) 169–182, https://doi.org/10.1111/j.1365-2486.1996.tb00070.x.

[75] A. Guevara-Escobar, E. González-Sosa, M. Cervantes-Jiménez, H. Suzán-Azpiri, M.E. Queijeiro-Bolaños, I. Carrillo-Ángeles, V.H. Cambrón-Sandoval, Machine learning estimates of eddy covariance carbon flux in a scrub in the Mexican highland, Biogeosciences 18 (2021) 367–392, https://doi.org/10.5194/bg-18-367-2021.

[76] S. Hassan, P. Inglese, L. Gristina, G. Liguori, A. Novara, M. Louhaichi, G. Sortino, Root growth and soil carbon turnover in Opuntia ficus-indica as affected by soil volume availability, Eur. J. Agron. 105 (2019) 104–110, https://doi.org/10.1016/j.eja.2019.02.012.

[77] C. de P. Rezende, R.B. Cantarutti, J.M. Braga, J.A. Gomide, J.M. Pereira, E. Ferreira, R. Macedo, B.J.R. Alves, S. Urquiaga, G. Cadisch, K.E. Giller, R.M. Boddey, Litter deposition and disappearance in Brachiaria pastures in the Atlantic forest region of the South of Bahia, Brazil, Nutrient Cycl. Agroecosyst. (1999) 99–112, https://doi.org/10.1023/A:1009797419216.

[78] D. de L. Coêlho, J.C.B. Dubeux, M.V.F. dos Santos, A.C.L. de Mello, M.V. da Cunha, D.C. dos Santos, E.V. de Freitas, E.R. da S. Santos, Soil and root system attributes of forage cactus under different management practices in the Brazilian semiarid, Agronomy 13 (2023) 743, https://doi.org/10.3390/agronomy13030743.

[79] A. Bautista-Cruz, T. Leyva-Pablo, F. de León-González, R. Zornoza, V. Martínez-Gallegos, M. Fuentes-Ponce, L. Rodríguez-Sánchez, Cultivation of Opuntia ficus-indica under different soil management practices: a possible sustainable agricultural system to promote soil carbon sequestration and increase soil microbial biomass and activity, Land Degrad. Dev. 29 (2018) 38–46, https://doi.org/10.1002/ldr.2834.
[80] X.Z. Ma, L.J. Chen, Z.H. Chen, Z.J. Wu, L.L. Zhang, Y.L. Zhang, Soil glycosidase activities and water soluble organic carbon under different land use types, Rev. Cienc. Suelo Nutr. Veg. 10 (2010), https://doi.org/10.4067/S0718-27912010000200001.
[81] M.G. Johnson, The role of soil management in sequestering soil carbon, in: R. Lal, J. Kimble, E. Levine, B.A. Stewart (Eds.), Soil Manag. Greenh. Eff., first ed., CRC Press, 1995, pp. 351–364, https://doi.org/10.1201/9780203739310-29.
[82] A. Naorem, S. Jayaraman, R.C. Dalal, A. Patra, C.S. Rao, R. Lal, Soil inorganic carbon as a potential sink in carbon storage in dryland soils—A review, Agriculture 12 (2022) 1256, https://doi.org/10.3390/agriculture12081256.
[83] R. Khalidy, E. Arnaud, R.M. Santos, Natural and human-induced factors on the accumulation and migration of pedogenic carbonate in soil: a review, Land 11 (2022) 1448, https://doi.org/10.3390/land11091448.
[84] A. Maaoui, A. Ben Hassen Trabelsi, M. Hamdi, R. Chagtmi, F. Jamaaoui, G. Lopez, M. Cortazar, M. Olazar, Towards local circular economy through Opuntia Ficus Indica cladodes conversion into renewable biofuels and biochars: product distribution and kinetic modelling, Fuel 332 (2023) 126056, https://doi.org/10.1016/j.fuel.2022.126056.
[85] A. Maaoui, R. Chagtmi, B. Apicella, F. Cerciello, O. Senneca, A.B.H. Trabelsi, Calcium-rich biochar derived from cactus feedstock and its efficient adsorption properties for industrial dye, Appl. Sci. 15 (2025) 894, https://doi.org/10.3390/app15020894.
[86] A.I. Moreno-Calles, A. Casas, E. García-Frapolli, I. Torres-García, Traditional agroforestry systems of multi-crop “milpa” and “chichipera” cactus forest in the arid Tehuacán Valley, Mexico: their management and role in people's subsistence, Agrofor. Syst. 84 (2012) 207–226, https://doi.org/10.1007/s10457-011-9460-x.
[87] F.M. Pinheiro, P.K.R. Nair, Silvopasture in the Caatinga biome of Brazil: a review of its ecology, management, and development opportunities, For. Syst. 27 (2018), https://doi.org/10.5424/fs/2018271-12267.
[88] N. Sipango, K.E. Ravhuhali, N.A. Sebola, O. Hawu, M. Mabelebele, H.K. Mokoboki, B. Moyo, Prickly pear (Opuntia spp.) as an invasive species and a potential fodder resource for ruminant animals, Sustain. Switz. 14 (2022), https://doi.org/10.3390/su14073719.
[89] R.T. Shackleton, A.B.R. Witt, F.M. Piroris, B.W. Van Wilgen, Distribution and socio-ecological impacts of the invasive alien cactus Opuntia stricta in eastern Africa, Biol. Invasions 19 (2017) 2427–2441, https://doi.org/10.1007/s10530-017-1453-x.