



Modeling the optimal grazing regime of *Acacia victoriae* silvopasture in the Northern Negev, Israel

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ABSTRACT

Silvopasture, the planting of suitable tree species in pastures, can improve the sustainability and productivity especially in dry rangelands. While recent studies provide information on the effects of different tree compositions on biological productivity, water and soil protection, additional parameters such as fodder production by the trees or the impact of silvopasture on the grazing potential themselves have rarely been addressed. We determined fodder production in *Acacia victoriae* woodland and savanna by measuring annual vegetation and tree biomass growth. We developed mathematical models for calculating the vegetative biomass available for grazing. In order to get accurate estimation for the grazing capacity, we differentiated between the grazing and the browsing fodder availability, and adapted the model to the most abundant grazers in the Negev, goats and sheep. Grazing capacity for sheep and goats was twice bigger in *A. victoriae* woodland than in the adjacent sustainably managed shrubland and four times higher than in degraded shrubland. The mathematical model presented in this paper can be applied in order to plan and realize high yielding and sustainable silvopasture in arid environments resistant to degradation and desertification while providing adequate fodder reserves during drought years.

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1. Introduction

Grazing is one of the major agricultural applications in arid areas and one of the major sources of food and income for local residents (Sidahmed, 1996). However grazing is mostly unrestricted and uncontrolled leading to rapid degradation and desertification of arid rangelands. Over one billion hectares of dryland (arid, semiarid and sub-humid) are considered degraded, mostly due to overgrazing (Dregne, 1978; Malagnoux, 2007). As a result, areas available for sustainable agri-pasture are shrinking with human and livestock populations steadily increasing (Barbier and Hazell, 1999). The regular droughts occurring periodically in drylands thus lead to repeated famine and loss of most livestock. These challenges could be overcome by applying afforestation in the form of silvopasture using browsable dryland trees (Wilkie, 2010). Planting of drought resistance trees with edible canopy biomass encourages flora growth underneath their canopy due to improvement of nutrient

cycling and improved water exploitation (Hazra and Singh, 1994; Leu et al., 2011; Scholes and Archer, 1997).

In fact, formation of silvopastures could be an effective tool in transforming livestock grazing into an ecologically sustainable process. Silvopastures hold great potential in rehabilitation of degraded dryland, provision of fodder and tree products (Samra et al., 1999), and the establishment of significant carbon sinks (Leu, 2005, 2010; Steinfeld et al., 2006). Several studies have been carried out on planting, species composition and management techniques of arid woodlands (Mbwambo, 2004). Additionally, several guides were written on establishing of 'Fodder bank' for grazing (Roshetko, 1994). Most of this work focused on the annuals and shrubs underneath and nearby the trees canopies (Ffolliott et al., 2008; Shaw and Kernot, 2004). The vegetative biomass of trees and evergreen shrubs in such systems can be regarded as the major source of fodder in the diet of browsers and grazers (Bergström, 1992; Walker, 1980) especially under drought conditions. Israel's land management authority, JNF-KKL (<http://www.kkl.org.il/eng/>), has planted *Acacia victoriae* (Ladiges et al., 2006) in the Northern Negev, Israel between 1990 and 1995, in order to rehabilitate degraded rangelands, increase the biological productivity and provide fodder for goats (*Capra aegagrus hircus*) and

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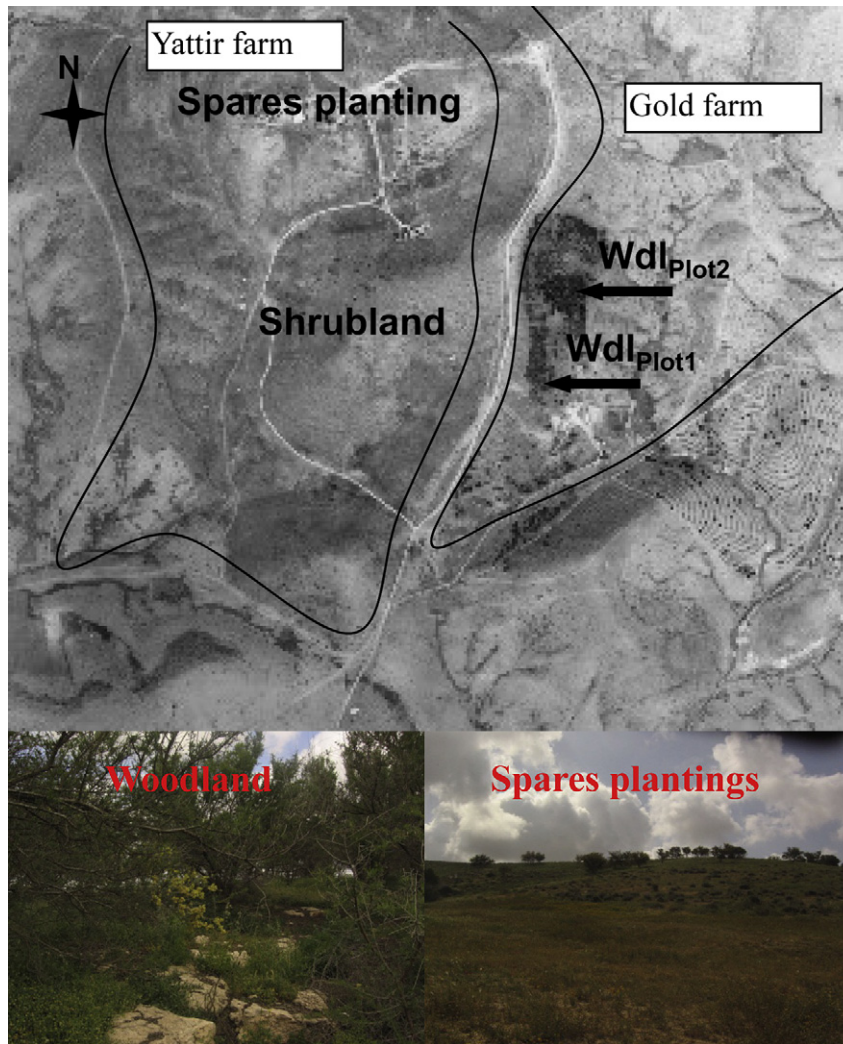


Fig. 1. Aerial photographs of the planting areas and research plots, in 2007. The Israeli national agency for geodesy cadaster, mapping and geographic information, Tel – Aviv. Below: Left, Woodland plot 2; Right, Sparsely planted area. Photos: A. Mor-Mussery.

domestic sheep (*Ovis aries musimon*) in this arid area.¹ We measured the biomass available for grazing in *A. victoriae* woodlands and savanna, and applied a mathematical model that allows calculating the total biomass of annuals inside the woodlands separate from the edible vegetative biomass of trees (Walker, 1980). This model integrates field observations on the grazing behavior of goats and sheep; scenarios with different proportions of grazers and browsers were analyzed. Overall, the model developed in this study could be further applied for determining optimal grazing regimes in additional arid locations, inhabited with other tree species.

Our model was tested in a representative area in Chiran forest. This area includes *A. victoriae*² woodland (density of 200–400 trees per hectare) and other sparsely planted trees planted in 1992–1993 grazed and subject to sustainable grazing. A nearby conserved shrubland plot served as a control for comparing productivity and annual fodder availability, and determining the long term fodder reserves created by the silvopasture approach.

¹ Lately JNF drastically decreased the plantings of this species, due to the invasiveness concerns (Wilkie, 2010). Of note, our observations do not confirm this suspicion (unpublished data).

² Species was identified by Dr. Bertrand Boeken, Ben Gurion University.

2. Materials and methods

2.1. Location and planting history of the study area

Data were collected North-East of Beer Sheva in Israel, near the towns of Meitar and Hura, in a 1 km² area (N 31°19'25", E 34°59'05", Fig. 1) with an elevation of 460–480 m (Fig. 1). For the last ten years (2001–2010) average precipitation at the site is 232 mm when averaging the data from the two nearest sampling stations of the Israeli Meteorological Service (www.ims.gov.il), Beer Sheva (185 mm, 18 km south west, elevation 300 m) and Yattir Forest (279 mm, 8 km north-east, elevation 680 m). The soil in the area is defined by the United States Department of Agriculture (USDA) guide as Sandy loam/Sandy clay loam type (USDA, 1999). The entire area was heavily grazed till 1993. Afterward, several family farms were established, including the Gold and Yattir farms where the research took place (for review on the agricultural farms in the Northern Negev see Olsvig-Whittaker et al., 2006). These farms are geographically close and have the same surface parameters. Part of those farms has been planted in 1993–1994 by the Jewish National Fund (JNF). Savanna trees species were planted in order to rehabilitate the soil and restore the area for grazing purposes. Inside these farms we located two areas occupied by *A. victoriae* (Ladiges et al., 2006). This tree is

particularly suitable for grazing in arid environments in Israel as it increases soil nutrient and soil water availability and facilitates herbaceous vegetation growth (Leu et al., 2011). At Gold farm *A. victoriae* was planted as dense woodland (200–450 trees per hectare) in an area of about two hectares. These trees were also planted in Yattir farm in sparse form (less than 50 trees per hectare) in a total area of 10 ha, 1000 m west from the woodland. The trees were grown naturally, not pruned, and were exposed to low grazing intensity.

The following plots with different density of trees and grazing management were identified and used for our analyzes:

- Woodland (three plots were defined)
 - First plot* – surveyed area 360 m², density of 250 trees per hectare, cover of 116% (16% overlapping³).
 - Second plot* – surveyed area of 440 m², density of 450 trees per hectare, cover of 122% (22% overlapping).
 - Patches* – two uncanopied areas, each of ~25 m², inside the woodland surrounded by the *A. victoriae* trees were chosen for analysis due to their high herbaceous biomass cover and importance in the woodland (Honnay et al., 1999)
- Sparsely planted plot-
 - At Yattir farm, 10 trees planted at low density of about 25 trees per hectare (savanna), were chosen for our measurements.
- Control (two plots were defined)
 - Conserved* – An unplanted shrubland area of five hectares between the woodland and the savanna area, subject to restricted grazing.
 - Degraded* – An excessively grazed shrubland (complete removal of all biomass including shrubs by grazing animals every year) 300 m south of the woodland plots were chosen as a control plots for comparison of biomass production and available grazing days in unplanted areas.

2.2. Measuring of canopy's vegetative biomass density

For measuring the *A. victoriae*'s edible biomass we chose representative tree, and pruned from it's canopy a cube of vegetative biomass with volume of 0.125 m³ (using 50 × 50 × 50 cm iron frame).⁴ The biomass was dried for 48 h at 60 °C and weighted. Value was calculated as kg per m³.

2.3. Measurements of the above ground biomass

A. victoriae standing soil biomass was measured as described by Scholte (1992) (In case of *Acacia commiphora*). Other biomass was classified based on its origin: annual herbaceous biomass, 'tree fallout' (Dunham, 1989), and litter – undefined dry vegetative matter (Boeken and Orenstein, 2001). The samples were collected using iron frame (20 × 30 cm) in five random locations per each plot. They were taken in the end of the rainy season (April) when the herbaceous biomass reaches maximal weight. The collected samples were dried for 48 h at 60 °C, and were divided into monocotyledonous and dicotyledonous biomass and plant litter. Weight values were calculated per 1 m² as described by Sava (1994).

³ The tree cover was calculated by dividing the total sum of all the canopies in the area by the total area surface. The ratio was multiplied by 100 in order to present it as percentage. In case, the values were higher than 100%, it meant existence of overlapping canopies.

⁴ For this manuscript, due to technical limitations, we took a representative tree. For further use and comprehensive research it is recommended to check this value in different years and seasons and separately per each treatment.

2.4. *A. victoriae* shape measurements

In order to measure the shape parameters of *A. victoriae* – canopy length, height of tree and trunk diameter, we used a height meter stick and length meter tools. We also counted the number of branches beginning from the lowest points on the trees. The trunk diameter was measured generally at 50 cm height above the ground, or underneath the branching point. Finally, to determine the relationship between trunk's height, and diameter with its weight, we measured and weighted four full shaped and dried trees of different size found in the woodland.

2.5. *A. victoriae* N–P–K content

The contents of the key nutrients, N–P–K (Nitrogen, Potassium and Phosphorous, respectively) were determined in the major tree parts (leaves, pods and roots). The samples were cleaned and dried for 48 h at 60 °C (Sava, 1994). The dried samples were taken to the Gilat Field Service Labs[®] for the chemical analysis.

2.6. Calculus methodology

The following mathematical formulae were used to calculate the amounts of *A. victoriae* foliage available for grazing/browsing. These formulae were used to calculate shape and growth patterns of *A. victoriae*'s foliage, the edibles parts of the plant.

The following abbreviations were used:

Ht. – Height
Bm. – Biomass
Dm. – Diameter
Vol. – Volume

2.6.1. *A. victoriae* partial primary production

The most important parameter for evaluation the suitability for grazing is the edible biomass per tree. Another important parameter is the 'Partial Primary Tree Production' (*P. Production*) which is the ratio of the vegetative (edible) canopy biomass to total tree weight. To determine this ratio, we calculated the total tree weight which is the sum of the vegetative canopy biomass determined as described below ($Bm_{CanopyVegetative}$), and of the woody branches and trunk (Equation (1)). In our model, the branches and trunk weight ($Bm_{Trunk + Branches}$) was calculated based on tree's diameter (Dm_{Trunk}), as described in Section 3.4, as presented in Fig. 4E and Equation (2).

$$P.Production = 100 * \frac{(Bm_{CanopyVegetative})}{Bm_{CanopyVegetative} + Bm_{Trunk+Branches}} \quad (1)$$

$$Bm_{Trunk-Branches} = 0.003Dm_{Trunk}^2 + 1.8Dm_{Trunk} - 7.3 \quad (2)$$

Based on *A. victoriae* shape (Ladiges et al., 2006 and our preliminary observations), the major part of the canopy begins above the unbranched trunk of the tree. In order to achieve maximal accuracy, all the measurements related to the canopy's green vegetative biomass ($Bm_{CanopyVegetative}$) were calculated above the unbranched trunk.

In the framework of this model, we defined the following parameters: total height of the tree (Ht_{Tree}), the unbranched trunk height (Ht_{Trunk} ⁵), and the canopy height (Ht_{Canopy}). The canopy's

⁵ In cases in which the branching began at the ground level, we did all the measurements at 0.5 m height, as demonstrated in Fig. 5.

volume (Vol_{Canopy}) was calculated using the dome formula based on the values of the horizontal and vertical diameters (the average diameter value was used – Dm_{Canopy}), and the Canopy's height – Ht_{Canopy} (Equation (1)). These values were measured at the plots. The schematic representation of the calculations is illustrated in Fig. 5. It should be emphasized that all the calculations referred to time period in which the measurements were taken. These values may change as the plant matures.

$$Vol_{Canopy} = \frac{4}{6} * \pi * \left(\frac{Dm_{Canopy}}{2} \right)^2 * Ht_{Canopy} \quad (3)$$

The canopy included both green and inedible woody parts. The canopy's dry volume (Vol_{Dry}) was defined as the inedible part around the trunk (dead and leafless branches). It was calculated using the dome formula with height marked as Ht_{Dry} , and diameter marked as Dm_{Dry} (Equation (4)). The subtraction of the dry volume from the total canopy volume resulted in the determination of the vegetative volume. Subsequently, multiplying the result by the canopy's vegetative biomass density gave the canopy's vegetative biomass ($Bm_{CanopyVegetative}$, Equation (5)).

$$Vol_{Dry} = \frac{4}{6} * \pi * \left(\frac{Dm_{Dry}}{2} \right)^2 * Ht_{Dry} \quad (4)$$

$$Bm_{CanopyVegetative} = Bm_{Density} * (Vol_{Canopy} - Vol_{Dry}) \quad (5)$$

2.6.2. Biomass availability for grazing

Only part of the vegetative biomass is available for the grazer. In order to quantify the amount of the *A. victoriae*'s available vegetative biomass, we developed a methodology for isolating the green and accessible biomass (defined as 'edible' one) from all the tree biomass. This methodology was tested on the different plots. We noticed that some of the green part was also inedible due to its inaccessibility to the grazing animal (Lemus and Brown, 2008). Based on this definition, the canopy's inaccessible volume ($Vol_{Inaccessible}$) was defined as the upper part of the canopy above the height accessible to the grazing animal ($Ht_{Grazing}$). Wilson and Mulham (1980) found that for goat this height equals 2 m. Based on data from local farmers and preliminary observation we used this value also for sheep. The inaccessible volume was calculated using the dome formula with its height equal to the subtraction of the $Ht_{Grazing}$ from tree's total height (Equation (6)). The diameter of the inaccessible area ($Dm_{Inaccessible}$) was calculated using trigonometric relationship (Equation (7)). The edible volume (Vol_{Edible}) was calculated by omitting the *A. victoriae*'s dry and the inaccessible volumes (Equation (8)).

$$Vol_{Inaccessible} = \frac{4}{6} * \pi * \frac{Dm_{Inaccessible}^2}{2} * (Ht_{Total} - Ht_{Grazing}) \quad (6)$$

$$Dm_{Inaccessible} = \left(\frac{Ht_{Tree} - Ht_{Grazing}}{Ht_{Tree}} \right) * (Dm_{Canopy}) \quad (7)$$

$$Vol_{Edible} = Vol_{Canopy} - (Vol_{Dry} + Vol_{Inaccessible}) \quad (8)$$

The edible biomass per hectare was calculated by multiplying the average edible volume of tree with the canopy's vegetative biomass density, and trees' density in woodland-Density (Equation (9)).

$$Bm_{Edible} = Vol_{Edible} * Bm_{Density} * Density \quad (9)$$

Once the edible biomass was calculated, its rate of consumption could be determined for the practical needs of a given farmer. In this work we make distinction between consumption of annuals

(grazing), and that of perennials/trees vegetative biomass (browsing), as defined by Lemus and Brown (2008). This consumption is measured in units of Grazing (Browsing) days. Using these units a farmer can determine the maximal period of time which takes one grazing animal to consume all the edible biomass of a given area. This value could be mathematically extrapolated by farmer for herd of any size.

We have defined, based on literature, grazing and browsing days for goats and sheep – the most abundant Negev grazers, both consuming about three kg of dry biomass per head and day. We assumed that goats are satisfied with herbaceous biomass of 1 kg day⁻¹ (dry matter) and browsing perennial biomass of 2 kg day⁻¹ (dry matter); the respective values for sheep are assumed to be at least 2 kg day⁻¹ of herbaceous biomass and maximum 1 kg day⁻¹ of perennial biomass (Lemus and Brown, 2008).⁶ The amount of the grazing days was calculated by dividing of the amounts of available edible biomass by the daily grazing consumption. *A. victoriae* and other perennial edible biomasses were classified both as browsing consumption (Bergström, 1992).

2.6.3. Quantification of the renewed edible biomass

The calculation described in the former section relate to the total edible biomass of the *A. victoriae* woodland. If the grazers would consume all of it, the trees will not be able to restore their biomass (Kraaij and Ward, 2006). In order to calculate the available biomass for sustainable consumption; that allowing the trees' edible biomass to be renewed, we have made the following assumptions:

- All the tree parts grow in the same rate.
- The growth rate of the trees belonging to the same species is uniform from planting till maturity.
- If grazers consume no more than the yearly growth rate of the tree, then the tree will be able to restore its biomass.

In order to calculate tree growth in different directions, we separated the growth rates of the trees to diameter (Dm_{Growth}) and height (Ht_{Growth}). These values are related to the total height and diameter of the tree ($Ht_{(n)}$ and $Dm_{(n)}$, respectively). The initial planting values were assumed to be height of 1 m ($Ht_{Planting}$) and canopy diameter of 0.5 m ($Dm_{Planting}$) (data from the JNF nurseries). The annual growth rates for diameter and height were calculated as growth in percents compared to the previous year (Equations (10) and (11), respectively). The acronym 'n' denotes certain number of years after planting.

$$Dm_{Growth} = 100 - \left(100 * \sqrt[n]{\frac{Dm_{(n)}}{Dm_{(Planting)}}} \right) \quad (10)$$

$$Ht_{Growth} = 100 - \left(100 * \sqrt[n]{\frac{Ht_{(n)}}{Ht_{(Planting)}}} \right) \quad (11)$$

In order to get a representative value for the growth rate of the edible part, we averaged the growth rates of diameters (vertical & horizontal) and height. Subsequently, we multiplied this representative value by the edible biomass. As a result, we obtained the value of renewed edible biomass (marked as $Bm_{EdibleRenewed}$; measured in kg per hectare and per Year) (Equation (12)).

⁶ We assume that tree density as found in the plots do no affect on the accessibility of the grazers.

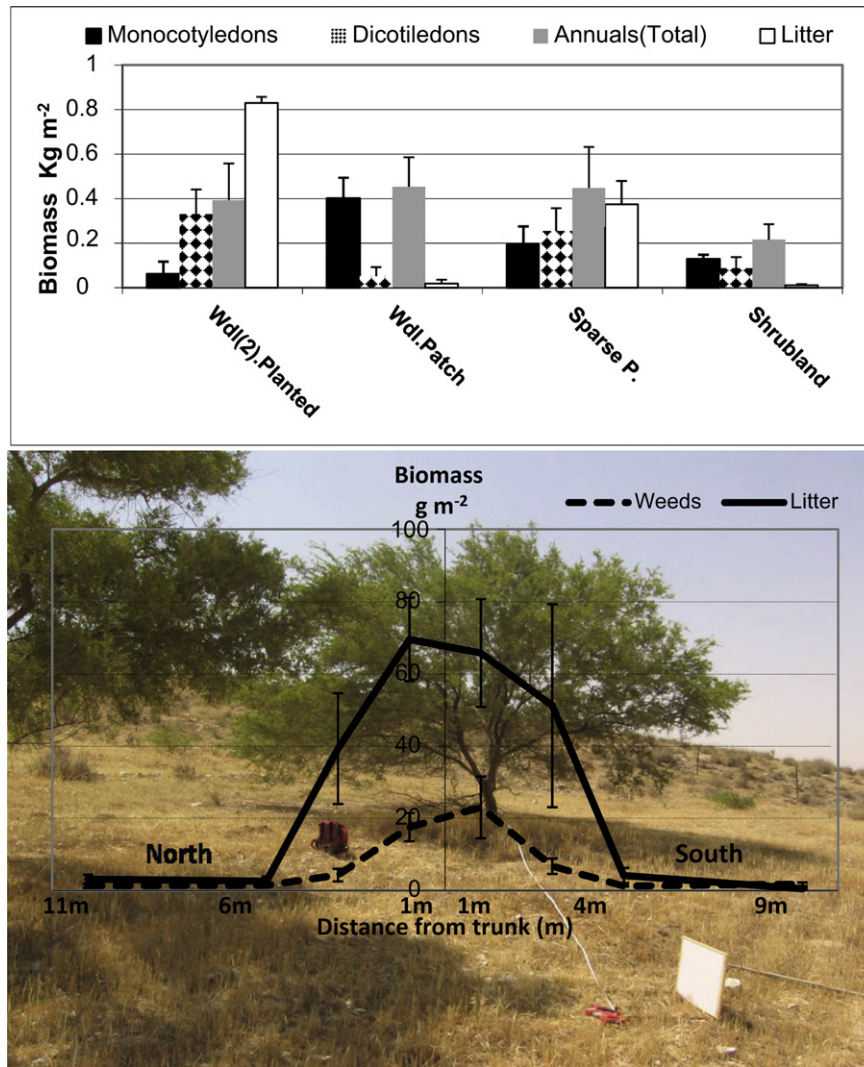


Fig. 2. Visual representation of the various tree parameters associated with *A. victoriae* biomass determination. Photo by A. Budovsky (location five km West from Meitar municipality, August 2011). $Vol_{Inaccessible}$ – Canopy's inaccessible volume (The volume above browser's ability to consume). Vol_{Edible} – Canopy edible volume (Net edible biomass). Vol_{Dry} – Canopy dry volume (The volume around the tree's trunk containing dead and un-leaved branches). $Ht_{Grazing}$ – Standing height of the grazer. Ht_{Tree} – Tree total height (from ground till the highest branch). Ht_{Dry} – Canopy dry height (trunk segment containing dead and un-leaved branches). Dm_{Canopy} – Canopy diameter (an average of the vertical and horizontal canopy diameter above trunk). Dm_{Dry} – Canopy dry diameter (measured at the bottom of the dry volume). $Dm_{Inaccessible}$ – Canopy's inaccessible diameter (an average of vertical and horizontal diameter, measured in the maximal accessible height for the grazer).

$$Bm_{EdibleRenewed} = \frac{1}{3} \sum \left(\frac{Dm_{Growth}}{100}, \frac{Dm_{Growth}}{100}, \frac{Ht_{Growth}}{100} \right) * Bm_{Edible} \quad (12)$$

3. Results

3.1. Distribution of the above ground biomass by plots

The results of biomass analysis in the different plots indicated that the amount of litter was distributed in the following decreasing order (from highest to lowest): the planted woodland, underneath the canopy of the sparsely planted trees, Woodland (patches), conserved and degraded shrubland (Fig. 3A). A similar tendency was observed in case of annual herbaceous biomass. The highest amounts of the dicotyledonous species were found underneath the *A. victoriae* canopy in the Woodland and underneath sparsely planted savanna trees. In contrast, the highest amounts of the monocotyledonous species were found outside the canopy of the *A. victoriae*. All these values were higher than those of the

uncanopied areas in the sparsely planted plot. A gradual decrease in herbaceous biomass from the tree trunk to outside (11 m long gradient) was observed (Fig. 3B). This change occurred in parallel to the decrease in litter contents and was most pronounced in drought years as 2009 when those data were collected. Higher biomass was observed (Fig. 2) in the woodland's patch plots (Woodland_{Patch}) as compared to the shrubland area. Similar effects were described by Honnay et al. (1999).

Annual total herbaceous biomass measured in an average rainy season (2010) in the different plots and per single savanna trees are summarized in Table 1, and also expressed in small ruminant (goat or sheep) grazing days. The yearly annual herbaceous biomass in woodland plots was thrice higher than that of degraded shrubland (4–4.5 versus 1.50 ton per hectare, respectively) and 50% higher than the annual biomass in conserved shrubland, at average precipitation. Expressed in grazing days for goats and sheep, the woodland plots provide up to 1500 grazing days from annual biomass alone, while the degraded shrubland provides only 500 days. It is however generally agreed that

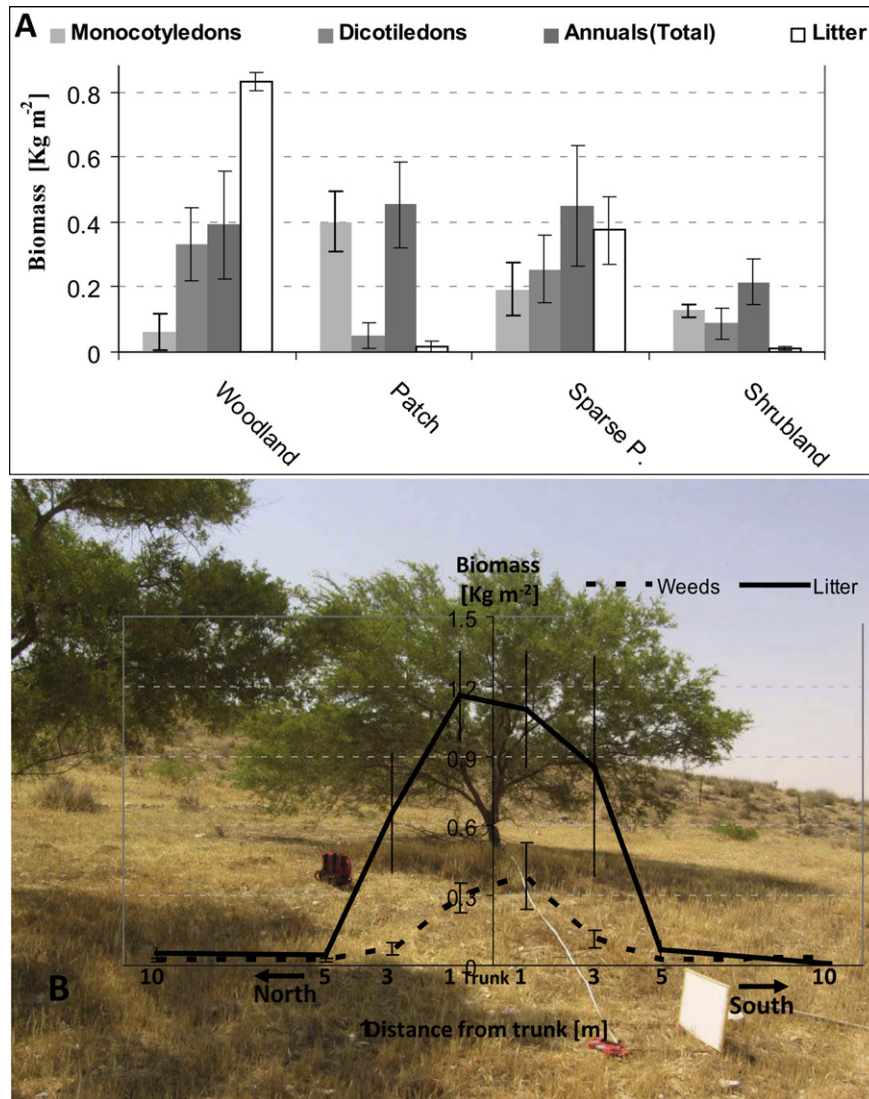


Fig. 3. (A) Above ground herbaceous biomass separated into monocotyledonous and dicotyledonous annual species (gray columns) and litter (white column), March 2010. 'Woodland': underneath *A. victoriae*'s in the woodland. 'Patch': in woodland patches. 'Sparse P.' Underneath sparsely planted trees in shrubland. 'Shrubland' Adjacent unplanted shrubland. (B) Gradual changes in the amounts of herbaceous biomass (dotted line) and litter (straight lines) from trunk (0–10 m distance gradient) into the open shrubland in the Savanna area (North–South direction), in kg per m², March 2009.

complete consumption of the available biomass in shrublands leads to degradation and desertification, while the tree litter provided in woodlands or savanna can prevent this and allows for more sustainable grazing (Leu et al., 2011). Under drought conditions the difference between wooded plots and open shrubland were much bigger (Fig. 3B).

Table 1

Available biomass for grazing from annual herbaceous vegetation in different shrubland and planted plots, and resulting maximal grazing days for small ruminants (sheep or goats).

	Conserved	Degraded	Woodland	Sparse planting	Patches
Annual herbaceous biomass [ton ha ⁻¹]	3.15	1.53	3.92	6.3	4.5
Maximum grazing days [Nr. per hectare]	1050	510	1306	2	1500
				[Nr. tree ⁻¹]	

Of note, in the calculations of the grazing days we refer to the total consumption of three kg per head per day for both ruminants.

3.2. The effects of the different tree densities on *A. victoriae*'s shape

Comparison of the first woodland plot (Woodland_{Plot1} with density of 220 trees per hectare) to the Woodland second plot (450 trees per hectare) and Sparse planting demonstrated the effects of dense planting. Dense planting design caused reduction in the number of branches (Fig. 4A), caused increase in the height of trees (Fig. 4B), and led to reduction in size of the canopy area (Fig. 4C). Additionally, the diameters of tree trunks decreased (Fig. 4D) along with the weight of branches, as estimated based on the relationship between tree's trunk diameter and weight (Fig. 4E).

3.3. Content of nutrients in *A. victoriae* vegetative parts

In order to evaluate the suitability of *A. victoriae* for grazing, we measured its nutrients contents in the vegetative parts. The levels of Nitrogen, Potassium and Phosphorus were measured in the pods,

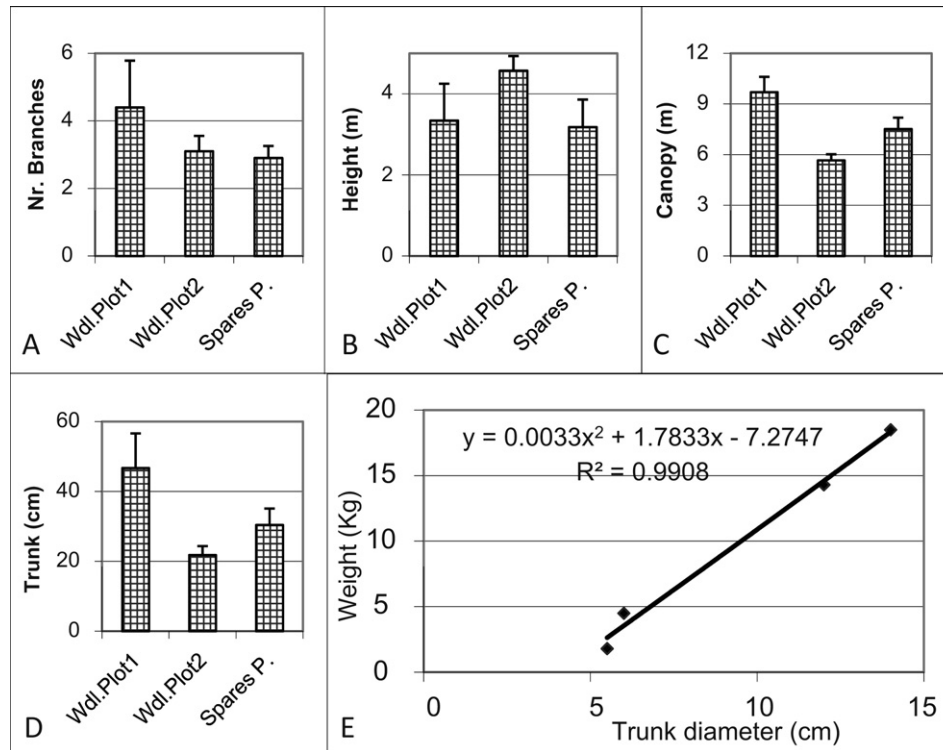


Fig. 4. Comparison of tree growth parameters between the Woodland and Sparsely planted trees (number of branches, trees' heights, canopies heights, trunk diameter). Wdl_{Plot1}, Woodland first plot; Wdl_{Plot2}, Woodland second plot; Spares P., Sparse planting. A – Number of different branches in the plots. B – *A. victoriae*'s total heights in the different plots (meters). C – *A. victoriae* canopy height in the different plots (meters). D – *A. victoriae* trunk height in the different plots (centimeters). E. – The relationship between trunk width (centimeters) and dry weight of branches (kilograms).

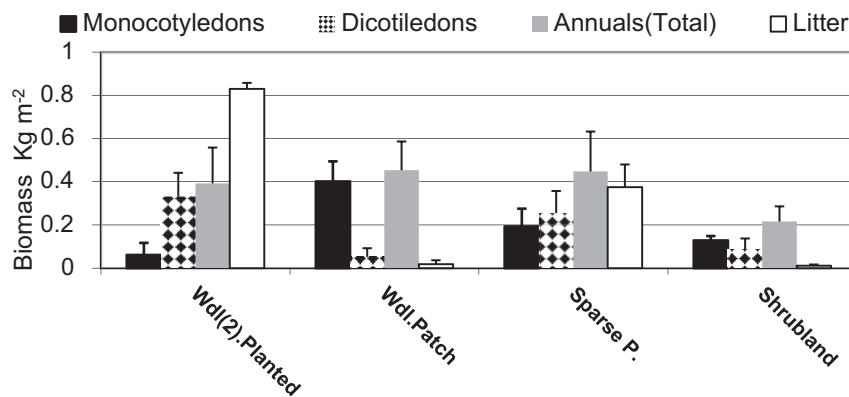


Fig. 5. Nutrient contents (N – Nitrogen, black column; P – Phosphorus, gray column; K – Potassium, white column) of the above ground biomass in different vegetative parts (pods, leaves, litter, roots) of the *A. victoriae*. Values measured in g per kg (Dry matter), mix of four replicates, February 2009.

leaves, litter and roots⁷ which are all consumed by the grazers. The highest amounts of these minerals were found in the pods and the leaves (Fig. 5) demonstrating the importance of the trees' fallout to grazing, and its contribution to the chemical balance of the soil.

3.4. The effects of the different plots on primary production

In order to compare the available tree biomass for browsing in the different plots, we calculated the tree's average vegetative

biomass and its partial primary production. The results are summarized in Table 2.

The collected results demonstrated the importance of these two parameters. The vegetative biomass per tree in both Woodland (plot2) and sparsely planted plots are almost the same (~45 kg per tree), but the utilization (reflected by the partial primary production) is 15% higher in the Sparsely planted plot than the Woodland second plot (48% compared to 33%, respectively). Thus, on average the sparsely planted plot has higher browsing usability per tree, despite having the same vegetative biomass as the Woodland.

Of note, For designing silvopastures, except the browsing usability value, factors as number of trees and placement location have to be taken into concern.

⁷ Field observations of goats are demonstrating the roots edibility of wide range of trees and shrubs (see also Harrington, 1976).

Table 2

Vegetative Biomass (kg per tree) and partial primary production (%) from total tree's weight in different plots.

	Wdl _{Plot1}	Wdl _{Plot2}	Sparse P.
Vegetative biomass [kg tree ⁻¹]	42.5	19.36	45.55
Partial primary production [%]	33.8	36.9	47.67

Wdl_{Plot1}, Woodland, first plot (density 220 trees per hectare).

Wdl_{Plot2}, Woodland, second plot (density 45 trees per hectare).

Sparse P., Sparsely planted trees (Yattir farm).

Table 3

Browsing biomass in the different plots.

Plot	Total browsable biomass		Sustained yearly browsing yield	
	Biomass	Browsing days	Biomass	Browsing days
Woodland (Plot1) (220 trees ha ⁻¹)	6.75 ton ha ⁻¹ 30.7 kg tree ⁻¹	3375 days ha ⁻¹ (Gt) 6750 days ha ⁻¹ (Sh)	0.9 ton ha ⁻¹	450 days ha ⁻¹ (Gt) 900 days ha ⁻¹ (Sh)
Woodland (Plot2) (450 trees ha ⁻¹)	7.0 ton ha ⁻¹ 16.4 kg tree ⁻¹	3500 days ha ⁻¹ (Gt) 7000 days ha ⁻¹ (Sh)	0.8 ton ha ⁻¹	400 days ha ⁻¹ (Gt) 800 days ha ⁻¹ (Sh)
Sparse planting	35.1 kg tree ⁻¹	18 days tree ⁻¹ (Gt) 36 days tree ⁻¹ (Sh)	4.5 kg tree ⁻¹	2 days tree ⁻¹ (Gt) 5 days tree ⁻¹ (Sh)
Shrubland	3.1 ton ha ⁻¹	1500 days ha ⁻¹ (Gt) 3000 days ha ⁻¹ (Sh)	0.6 ton ha ⁻¹	200 days ha ⁻¹ (Gt) 300 days ha ⁻¹ (Sh)

The biomass and the browsing day values were calculated per hectare and per tree for a year, and for goats ('Gt') and domestic sheep ('Sh'), separately, both totally and annually renewed.

Fodder consumption of goats was calculated based on daily browsing consumption of two kg per day (From total three kg needed*) and for sheep, one kg per day (from total three kg needed). *The remaining has to be supplied as annuals and/or straw.

Notes: a. The edible part of the perennials was estimated as ten percents of the total biomass (based on NDVI values, data not shown). b. The biomass per tree was estimated based on canopy's area and value per m².

3.5. Biomass availability for grazing in the different plots

Comparison between the weights of the edible tree parts demonstrated the existence of relationship between planting density and edible biomass. In the more sparsely planted Woodland the weight of the edible biomass per tree was much higher than in the dense ones (35.1 kg per tree in Woodland_{Plot1} versus 16.4 kg per tree in the Woodland_{Plot2}). Yet, the high densities of woodland_{Plot2} compensated, and so the total biomass was almost the same for both plots (as seven ton per hectare). The Woodland (plot2) values were similar to those of the sparsely planted area, and are in agreement with findings of Hegazy et al. (2008) in regard to the relationship between planting density and biomass.

The perennial woodland biomass was more than twice higher (220%) than that of the shrubs in adjacent shrubland (Lemus and Brown, 2008). Of note, the same proportion was found in case of the available browsing days at the woodlands and the shrublands (3375 versus 1500 goat browsing days per hectare, respectively). However, sustainable grazing in shrublands prohibits consumption of the perennial shrubland biomass (Shachak et al., 2008), which is also often toxic or inedible,⁸ this in contrast to *A. victoriae* biomass.

3.6. Calculating the renewed *A. victoriae* edible biomass

As already mentioned consumption of all the edible biomass in the woodland may disable full renovation in the next year, and damage the sustainability of the silvopasture. For calculation of the renewed edible biomass, we assumed that grazing consumption lower than that of one year growth of the woodland will not endanger the restoration of silvopasture to its primary stage. The average annual growth was found to be 13% in the Woodland_{Plot1} and the Sparsely planted area, as compared to only 10% in the Woodland_{Plot2}. The highest renewed biomass per tree value was

observed in the sparsely plated trees sector – 4.5 kg per year. In case of woodlands, the higher value per hectare was observed for Woodland's first Plot (880 versus 770 kg per hectare in the second one, respectively). The renewed tree biomass provided some 300 grazing days in addition to the grazing days derived from annual biomass (Table 3), so that in conclusion a *A. victoriae* woodland can provide almost 2000 grazing days sustainably, compared to 500 in degraded shrubland.

The importance of the silvopasture trees becomes much greater under drought conditions. The available accessible tree biomass provides several thousand grazing days of fodder reserve, while the trees also facilitate annual biomass growth under drought condition (Fig. 3B). Thus, *A. victoriae* woodland in contrast to open shrubland allows maintaining herd size throughout drought seasons, though for drought conditions goat herds become favored due to their higher preference for browsing.

4. Discussion

This paper is the one of the first attempts to describe the patterns of *A. victoriae* growth and their effects on biomass availability for grazing. The results of this work clearly demonstrate the positive effect of *A. victoriae* on sustainable rangeland management. This is remarkable taking into account degradation of the area of study till 1992–1993 due to heavy grazing. The woodland plots had much higher biomass and productivity than the other plots (Tables 1 and 3, Fig. 2A; Leu et al., 2011). This notion was also supported by observation that there was a gradual decrease in biomass moving away from the tree trunk to the surrounding (unplanted) environment (Fig. 3B), especially pronounced in drought years. Such a decrease could be explained by drop in litter content outside of the trees (Boeken and Orenstein, 2001).

A. victoriae planting also had a profound effect on types of vegetation growing in the studied plots. This is important as different animal species consume different types and amounts of vegetative fodder (the fodder proportions are difficult to estimate accurately⁹). As expected, the *A. victoriae* woodland plots have all

⁸ We noticed that in the area of study most of the shrubs are poisons or inedible to the ruminants (e.g. *Thymelea hirsute*) and will not be eaten.

⁹ Few attempts have been made in order to get accurate estimation of fodder consumption. They were also partial. Two important trials were done by Lemus and Brown (2008) who averaged and divided the fodder consumption to the following components: 'Straw consumption' (grass), 'Grazing' (annuals) and 'Browsing' (evergreen shrubs and tree's vegetative biomass). In another study, Ffolliott et al. (2008) divided the annual grazing (in Oak savanna) to dicotyledonous and monocotyledonous species consumption along the year (for different grazers).

the conventional fodder components (Fig. 2). What was surprising is that besides these conventional biomass components, we also identified rarer species such as *Malva nicaeensis* and *Salvia fruticosa* (Tanji and Nassif, 1995). Thus, *A. victoriae* planting led to increased biodiversity in the silvopasture plots.

We also demonstrated that planting density of *A. victoriae* had a substantial influence on type and variability of the underlying vegetation. Raising the density allowed increasing the dicotyledonous biomass and its variability, while lowering it increased the monocotyledonous species biomass and made the planted trees more grazing efficient (sparsely planted plots). We also noticed that the planting densities affected the shape parameters of *A. victoriae* trees (height, diameter, number of branches, etc.)¹⁰. This in turn may affect the trees' biomass and grazing regimes and will allow the farmer planning of the desired average tree biomass in the long term. Thus, type, contents, and quantity of fodder could be manipulated by choosing initial planting densities by the farmer. Subsequently, this initial choice may influence the amount of available grazing/browsing days for either goats, sheep, or any other grazers.

Data from Australia (which is the original homeland of the *A. victoriae*) emphasized the high nutritional value of *A. victoriae* for the animals (Ladiges et al., 2006). Our observations and data from local farmers confirmed this notion. We also measured high Nitrogen, Phosphate and Phosphorus contents in the *A. victoriae* woodlands, highlighting its contribution to the enrichment of the mineral content of the arid soils (Leu et al., 2011). In order to better elucidate the nutritional value of the *A. victoriae* in the silvopasture further nutritional and toxicity tests should be carried out on the grazing animals (Tefera et al., 2007).

Besides the nutritional value, the primary parameters that define the suitability of tree species for grazing are the vegetative biomass and partial primary production. As already mentioned most of the previous works dealt with trees in nature with unknown age. While several methods are used for rough estimation of the planting age (for review see Duncan, 1989), they are not accurate. Under such a restraint only the 'partial primary production' could be calculated, as its calculation is based on the already known parameters (Abdul-Hamid et al., 2009). We found that the 'partial primary production' in sparse planting trees was ~50% in the case of *A. victoriae*. Dunham (1989) reported 'partial primary production' of 70% for *Acacia albida*, but in his calculation he also included pods. If we would have taken the same measure as Dunham, we would also obtain the same value of 'partial primary production'. Interestingly, these values were a little higher for *Betula alnoides* which grows in temperate climate (Hughes, 1971). It has to be noted that the *Acacia* species are known for their high water use efficiency. For example, in case of *Acacia nilotica*, Zahid et al. (2010) found that the 'water use efficiency' was 0.32 g L⁻¹ which is higher than that of most arid species tested. The minimal yearly water consumption of this *Acacia* was only 58.3 L.

The novelty of this work lies in suggestion of a mathematical model that allows calculating the available biomass for grazing. The applicability of this model was demonstrated by us both in case of a single tree and the total plot. In all cases, planted *A. victoriae* trees significantly increased the possible livestock grazing days per area, by contributing edible tree biomass (10–20 kg per planted tree, or 5–10 grazing days), doubling the herbaceous biomass and providing tree litter also useful as fodder, so that in summary each tree planted provides at least 10–20 additional grazing days per year.

During drought years the trees provide an additional fodder buffer allowing more intensive browsing as well as trimming of higher up inaccessible canopy biomass that can be restored during following more humid years. This property is of extreme importance to long term sustainability of dry rangeland exploitation, as significantly larger herds can be fed during the regularly occurring drought years. The *A. victoriae* woodlands as described here could feed a goat herd through two successive drought years using tree vegetative biomass and annual biomass near the trees, while shrubland would feed only a fraction of a similarly sized herd under drought (Fig. 3B). It must be stated that tree litter has not been taken into account for our calculations, though part of it can serve as fodder as well, even increasing the advantages of woodland further.

We also showed using the model that in some cases the edible biomass could be higher at certain densities. The model is very flexible and its various parameters such as tree's growth rate, the grazer monthly consumption, other grazer species, and alternative type of fodder could be easily calculated and studied in the framework of other agri-pastoral environments. For easing the calculations, we based the model on exponential and equal growth rates. Additional factors such as climate changes along with events occurring after the plants reach maturity were not taken into account due to difficulties in their prediction (for review of other models see Constable and Friend, 2000). Nevertheless, these factors could be integrated in further studies.

Altogether, we believe that this model which takes into account both the ecological state of a given silvopasture, and the grazers' demands can optimize the economical use of arid area together with avoiding desertification.

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¹⁰ These parameters can be changed also by planned pruning, as described by Chandrashekhara (2007).

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