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Maginot Ngangyo Heya
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Rahim Foroughbakhch Pournavab
Artemio Carrillo-Parra

Biology, Productivity, and Bioenergy of Timber-Yielding Plants

An Experimental Technology

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Maginot Ngangyo Heya
Faculty of Biological Sciences
Universidad Autónoma de Nuevo León
San Nicolás de los Garza, Nuevo León, Mexico

Rahim Foroughbakhch Pournavab
Faculty of Biological Sciences
Universidad Autónoma de Nuevo León
San Nicolás de los Garza, Nuevo León, Mexico

Ratikanta Maiti
Faculty of Forestry
Universidad Autónoma de Nuevo León
Linares, Nuevo León, Mexico

Artemio Carrillo-Parra
Instituto de Silvicultura e Industria de la Madera
Universidad Juárez del Estado de Durango
Durango, Durango, Mexico

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About the Authors

Maginot Ngangyo Heya graduated from the Faculty of Sciences of the University of Yaoundé I, Cameroon, with a master's degree obtained with the mention "très bien" in botany-ecology; since February 2017, he is doctor in sciences with the honorific mention "summa cum laude" in management and administration of plant resources from the Faculty of Biological Sciences, Universidad Autónoma de Nuevo León Mexico. He has published six scientific articles in indexed journals and three book chapters and has participated in several national and international congresses. He has conducted research stays at the Faculty of Resources Management, University of Applied Sciences and Arts (HAWK), Göttingen, Germany, and at the Faculty of Engineering in Wood Technology, Michoacana University of San Nicolás de Hidalgo, Morelia, Michoacán, Mexico. He is a reviewer for indexed journals, including the *International Journal of Agricultural Policy and Research*, the *British Journal of Pharmaceutical Research*, and *Ciencia UANL*. His lines of research are related to renewable energies with emphasis on the quality and characterization of solid biofuels, sustainable development, climate change, and forest ecology.

Ratikanta Maiti is a renowned botanist of international repute who specializes in crop physiology and botany. He worked for 9 years as a senior botanist at the Jute Agricultural Research Institute, Barrackpore (ICAR), Kolkata, West Bengal, and for 10 years as a senior plant physiologist in ICRISAT, Patancheru, AP, India. Subsequently, Dr. Maiti was senior Professor and senior research scientist at CONACYT, Mexico, for 18 years and in two universities in Mexico for 20 years. During his scientific career, he has developed innovative techniques for the screening of salinity and drought of several crops. As author of more than 30 books, he has won several international awards, including the

International Scientist Award offered by IBC, Cambridge, the 2003 Ethnobotanist Award sponsored by Friends University, USA, and UNDP, and the 2008 gold medal for India offered by ABI.

Rahim Foroughbakhch Pournavab is a botanist from the University of Tabriz Iran, with a doctorate degree (Ph.D.) in quantitative applied plant ecology from the National Scientific Center (CNRS France) and a post doctorate degree in agroforestry systems from the National Agronomic Center (INRA France).

He is researcher-professor at the Silvicultural and Removable Resource Management Institute of the Universidad Autónoma de Nuevo León (UANL), Mexico (1981–1990), a member of the Mexican National Researcher System (1989–2030), coordinator and member editor of the journal *Ciencia UANL*, and chief of the Botany Department in the Faculty of Biological Sciences at the UANL, Mexico.

He is also a research scientist and professor in the Faculty of Biological Sciences at the UANL, Mexico (1993–present), and has received awards from CONACYT and UANL, Mexico for his research contributions. For 4 years, Dr. Pournavab has been research advisor and coordinator at Multiceras S.A. de C.V. industry in a research project on seed biology, genetic productions, and vegetative propagation of candelilla (*Euphorbia antisyphilitica* Zucc.) under abiotic stress in arid zones of Northeastern Mexico.

His basic objective is to create new and low-cost technology for research and development and to find techniques and solutions for enhanced forestry productivity. He has successfully published more than 200 papers in national and international journals, conferences, symposia, and seminars, including articles and books/chapters at the national and international levels.

Artemio Carrillo-Parra received his Ph.D. in biology and wood technology from the Georg-August Universität Göttingen, Germany, in 2007. He is a member of the SNI (National System of Researchers), Level I.

He is professor with Profile PRODEP, professor-researcher, and coordinator of the Wood Technology and Industry Area of the Institute of Forestry and Wood Industry at Juárez University of the State of Durango, Mexico. He is director and advisor of about 30 doctoral theses and master's and bachelor's degrees. Further, he is a reviewer of indexed journals, including the *American Journal of Plant Sciences*, the *Journal of Wood Chemistry and Technology*, *Madera y Bosques*, *Revista Mexicana de Ciencias Forestales*, *Nova Scientia Electronic Magazine*, and the *Scandinavian Journal of Forest Research*.

Chapter 1
Timber-Yielding Plants of the Tamaulipan Thorn Scrub: Forest, Fodder, and Bioenergy Potential

Abstract The current energy crisis generated growing interest for alternatives to fossil fuels, presenting lignocellulosic materials as promising resource for sustainable energy. Mexican scrubs represent important forest resources to satisfy the population's needs. There, forage potential was determined, to establish strategies for vegetation optimal use; forest potential, to assess biomass productivity; and bioenergy potential, to encourage new, promising, and integral use of this resource. Two locations were selected, experimental plantations and natural areas, where shrub coverage, timber volume, leaf biomass, litterfall, and chemical composition were determined. The data were statistically analyzed using SPSS program, applying Tukey's test. Native vegetation of *E. ebano* and *A. berlandieri* presented greater coverage value (19.68 m^2/individual). The higher foliar biomass was recorded in summer (9029.322 kg ha^{-1}) with *E. ebano*. The litterfall accumulated more in spring with *A. berlandieri* (273.73 kg ha^{-1}) and *A. wrightii* (296.45 kg ha^{-1}). The timber volume was greater in plantations (0.8287 m^3/ha/year for *H. parvifolia* and 0.2740 m^3/ha/year for *E. ebano*) than in native vegetation (0.1468 m^3/ha/year for *H. pallens*, 0.1225 m^3/ha/year for *A. wrightii*, and 0.1200 m^3/ha/year for *A. berlandieri*). The inorganic elements varied in trunks (1.09–2.29%), branches (0.86–2.75%), twigs (4.26–6.76%), and leaves (5.77–11.79%), and the highest proportion occurred in Ca (57.03–95.53%), K (0.95–19.21%), and Mg (0.88–13.47%). The higher extractable contents (3.96–17.03%) were obtained in methanolic solvent. Lignin recorded ranks 28.78–35.84% (trunks), 17.14–31.39% (branches), and 20.61–29.92% (twigs). Calorific value ranks were 17.56–18.61 MJ kg^{-1} (trunks), 17.15–18.45 MJ kg^{-1} (branches), 17.29–17.92 MJ kg^{-1} (twigs), and 17.35–19.36 MJ kg^{-1} (leaves). Lignin showed moderately strong relationship ($r = 0.66$) with calorific value.

Keywords Forest potential • Fodder production • Phenology • Litterfall • Bioenergy • Timber-yielding plants • Tamaulipan thorn scrub

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1 Introduction

Mexico is a country well known for its rich forest resources (Cruz-Contreras 2012), occupying 11th world place in forest area with 70% of national territory and 26th place in forest production (SEMARNAT 2012). It is estimated to occupy 126.6 million hectares of forest surface among which 25.8 occupy forest, 8.8 of forest with secondary vegetation, 13.1 of tropical forest, and 21.2 of tropical forest with secondary vegetation, and 57.6 possess vegetation of arid zones (SEMARNAT 2010). In the arid and semiarid zones representing more than 50% of total surface of the country (Rzedowski 1991; INEGI 1997; González 2012), there exist large variations in climatic and edaphic conditions, which exhibit different types of extremely diverse plant communities in terms of composition, plant height, canopy cover, density, and associations (Battey 2000; Eviner 2003). In these communities, the scrub stands as the most abundant forest resource and historically the most utilized (García and Jurado 2008). This occupies an extension of 125,000 km^2 in the coastal plain of Mexican Gulf in Northeast of Mexico and extreme south of Texas, USA (Ruiz 2005).

The Mexican scrub communities have been classified from practical point of view as xerophytic scrub by Rzedowski (1978). This is based mainly on the origin of its structure and composition. This highly diverse ecosystem, consisting of trees, shrubs, and subshrubs, varies in density and also in plant height (Heiseke and Foroughbakhch 1985; Alanís 2006). It has been a provider of important plant products (Rojas 2013), which are used for a wide variety of purposes such as the production of forage, firewood, timbers, materials for construction, human food, and traditional medicine and extraction of spices (Foroughbakhch and Heiseke 1990). Besides, this resource is used for the production of charcoal and, above all, the establishment of crops and pasture (Correa 1996).

Although the Northeast Mexico scrub has provided great benefit to populations, the anthropic activities have caused loss of a large extension of vegetation leading to soil erosion and a decrease to its productivity. Since soil is the basic component of an ecosystem because of its influence on productivity, any attribute of vegetation related to the reduction of erosion and stability of soil surface characteristics should be measured primarily. In this respect, the plant canopy cover which offers the interception and absorption of rain drops favors the infiltration and reduces the flow of rainwater and loss of soils as well as vegetation soil stability (Branson et al. 1981; Gaither and Buckhouse 1983; Thurow et al. 1988; Simanton et al. 1991).

In this context, the increasing demand of the population for the products and services has motivated the plantations of forests, to supply timbers and its products to local and global markets, thereby contributing significantly to the rural and industrial progress (FAO 2013). From the viewpoint of technical perspectives, and on the basis of the knowledge on silviculture, economy, social aspects, and ecology, there are sufficient arguments to hypothesize that the plantations of forests in Mexico are viable options with possibility to contribute to the economic growth of the country (Zamudio Sánchez et al. 2010). Besides, the forest plantations favor the productivity of forests and at the same time reduce the pressure and the use of natural forests and also enable for better exploitation of areas which have been altered by the agricultural or animal husbandry (INE 2007).

This productivity of forests has direct relation with the biomass, which according to Ledesma et al. (2010) is a fundamental variable for tree. Its estimation is an important parameter for the application of models based on the growth of trees (West 1987; McMurtrie et al. 1989; Bassow et al. 1990; Korol et al. 1991). This is necessary for the studies on the production of vegetation, nutrient cycles, hydrology, habitat of wild fauna (animals), and patterns and occurrence of forest fire (Waring 1985; Long and Smith 1988). The majority of quantitative analysis on biomass potential in the wooded regions has only been referred to the tree stratum, leaving aside the bushy shrubs, excluding from its quantification, an important amount of biomass, present equally, both under woodland and open forest land (Sánchez et al. 2008). Mittelbach et al. (2001) recommend undertaking studies on shrub species which are the least studied in the world. Although the proportion of non-woody vegetation in total biomass of a forest may be very low, this does not mean that they are not important in their structure (Álvarez 1993). Therefore, the quantification of herbaceous biomass is of great importance from the viewpoint of forage which is considered to reach to 40% of the surface area of herbaceous strata (Benavides 1993). For greater precision in the estimation of biomass, the aerial biomass as well as necromass should be also considered, since according to McDicken (1997) and Marquéz et al. (2000), the necromass is one of the biomass compartments.

On the other hand, it is calculated that of the timber production of a tree, only 20% is exploited, but 40% is left in the field, which include branches, tips, and roots; the remaining 40% is wasted during the sawing process, in the form of chips from bark and sawdust (Enciso 2007). These residues are potential source of prime matter for the generation of energy by the process of silvicultural management or subproducts of the industry transformation (PNUMA 2010). Therefore, it is considered that the correct management of the forests and forest plantations and the utilization of the materials derived from wood industry are alternatives for the production of prime matter for the development and production of biofuels (Goche-Télles et al. 2015). According to the data provided by Wu et al. (2011), 50% of the population of the planet utilizes biofuels for obtaining heat, owing to the environmental politics that seek to reduce the pollution derived from the combustion of fossil fuels. In Mexico, firewood and charcoal represent the third place in volume of extraction, with 9.9% (SEMARNAT 2007).

For the determination of the main characteristics of the energy of these materials, the physical and chemical variables that define them should be considered. The chemical characteristics of the wood that mostly influence its behavior as biofuel are the elemental chemical composition, the chemical composition by compounds, and the calorific value (Camps and Marcos 2008). Under these premises and in search of improvement of bioenergy efficiency, it is of great importance to determine the yields and to evaluate the quality of biofuels from different components of timber species of the Tamaulipan thorn scrub, including twigs and leaves that are considered as residues and trunks and branches that are the most commonly used parts, generally more suitable for exploitation. At the same time, the knowledge of the characteristics of Tamaulipan thorn scrub would provide an integral vision of the silvicultural opportunities for adequate application in each area, considering the growth and the productivity for a good planning of the management, improvement, and utilization of these resources.

2 Objectives

2.1 General Objective

Analyze and determine the forest, forage, and bioenergy potential of five timber species of the Tamaulipan thorn scrub, which allow to demonstrate the environmental and economic benefits derived from its utilization as a source of renewable energy in the Northeast Mexico.

2.2 Specific Objectives

- Study the phenological variations of the timber-yielding species of the Tamaulipan thorn scrub, in relation to climatic conditions.
- Quantify the necromass (litterfall) of the tree-shrub stratum, for characterizing the variability of the soil-plant system as indicator for their sustainability.
- Quantify and characterize the herbaceous biomass for the establishment of an integral system and of greater precision in forage potential of the Tamaulipan thorn scrub.
- Determine the leaf biomass of the woody vegetation as simple tool for the monitoring and following process.
- Evaluate the growth and the volumetric production of the selected timber species of the Tamaulipan thorn scrub.
- Evaluate the quality as biofuels of different components of the selected timber species, both for the biomass without treatment and for charcoal.
- Determine correlations among ecological parameters with seasons, dendrological data, and bioenergetic parameters.

3 Justification

The consumption of energy in the world has increased constantly with increasing population and industrialization, being the derivatives of fossil fuel; the currently predominant energy sources, petrol and natural gas, are becoming limited resources which will be exhausted in some moments in the near future. Although there are debates on the exact year of the peak period of the production of petrol, it appears that it may occur before 2025, after which the production of petrol will start falling in the whole world (Campbell 2013). This exhaustible nature of the actual resources, associated with the greater demand of energy, has accelerated the search for alternative source energy to satisfy the demand of the society in sustainable manner. This situation has provoked an interest to find nonfossil, renewable, and low-contaminant fuels. The motivation of this change of posture is not only for the necessity to search an alternative to petrol owing to its finite character associated with an increase in demand for energy but also for care of the environments and a necessity to reduce the emission of greenhouse gases (Wackett 2008).

Other important aspects of renewable energies are, in addition to the environmental component, the backbone and social effect that these technologies can have. Therefore, they are considered as key technologies for various reasons beyond the energy security or the preoccupations of environments such as increase of divisas and socioeconomic conditions of rural sector (Demirbas 2008), owing to the creation of local employment and activation of the economy of these regions.

Most of the large energy-consuming countries are adopting very active policies aimed at a much greater use of biofuels for the coming decades (Kojima and Johnson 2005). In Mexico, they are looking at how to introduce biofuels into the energy matrix, in a sustainable manner with national producers, and thus be able to impulse the rural development (Valle and Ortega 2012).

The renewable energy production systems have delivered a reduction of contamination load generated by fossil fuels. In the case of biomass, there are other benefits such as promoting rural development and providing adequate waste treatment, in some cases polluting, or managing waste from pruning, thinning and waste from harvesting, limiting the propagation of fires (Rincón and Silva 2014). The use of residual forest products as fuel for biomass boilers is one of the solutions to facilitate the forest healths (IDAE 2007).

The most important sources of biomass are the areas of forest and crop fields; these produce residues which are generally left in the field (Camps and Marcos 2008). The forest industry generates large volumes of residues during the process of exploitation up to the obtainment of final product. It is calculated that the residues are 28% of the volume of harvested wood with bark in the forest, per cm^3 (Martín 2001). The forest residues derived from silvicultural activities and/or forest industries consist of branches, stumps (when they are not used due to economic reasons), bark, chips, and sawdust.

The energetic use of these forest residues, derived from silvicultural activities such as pruning and cleaning, sometimes not economically profitable, implies an integral management of the forest masses (Borja 2006). The high availability and low price of forest subproducts, sawdust, viruta, and wattage, among others, encourage the search for new productive alternatives. Bioenergy production is an economically and ecologically viable option (García et al. 2012). However, it is necessary to determine that these subproducts fulfill the international quality standards. For these, it is needed to evaluate moisture content (MC) and some physicochemical characteristics such as ash percentage and types and percentage of inorganic elements (García et al. 2012; Vassilev et al. 2012). The knowledge of the chemical compositions of different structures of the timber-yielding species is an important aspect, necessary to find alternative of the economic benefits that these resources provide for the different industries (García et al. 2004).

Beyond these qualitative aspects mentioned above, it is necessary to take into account the quantitative dimensions of the forest production for its better management, leading to the optimization of exploitation. The relevance of applying it to Tamaulipan thorn scrub lies in the interest of knowing the diversity of species that are part of the structure of this plant community and evaluates its productivity in order to be in a position for taking the best management decisions, seeking to take advantage of sustainable forage for wildlife.

The management of these resources must be based on the observation and interpretation of different characteristics, which allow estimating as precisely as possible the availability of fodder, understood as the amount of dry matter delivered daily to each animal. This is the starting point for a series of high-impact decisions on productive results in forage-based livestock systems, with the fundamental objective of establishing strategies that can be adapted by means of modifications according to the place and in order to achieve optimum management and utilization of the vegetation and wildlife. Therefore, the study and analysis of the vegetation cover should be the first step to follow. According to Wilson and Tupper (1982), the relevance of selecting vegetation cover as an indicator of the impact of some breeding practice is because any change in it is the first symptom of changes in environmental processes such as erosion, soil, and botanical composition. In addition, the coverage parameter indicates, better than any other parameters, such as abundance or dominance, occupied volume or soil surface covered by a species (Huss et al. 1986).

It is also considered the fall of litter, as something of great importance, especially where the vegetation depends on the recycling of nutrients coming from its deposition (Bernhard-Reversat et al. 2001). At the same time, the phenological changes (the appearance of new leaves, flowers, and fruits) represent adaptation to biotic and abiotic factors (Van Schaik et al. 1993), under existing climatic conditions. These parameters may exhibit reliable instrument for the evaluation of the native populations of the species of Tamaulipan thorn scrub and its associated species and could serve as the base for the elaboration of adequate management or for modification of actual practices of exploitation and at the same time for the conservation, improvement, and sustainable use of these important forest resource ecosystems in arid and semiarid regions (Meza 2002).

4 Review of Literature

4.1 General Aspects of Tamaulipan Thorn Scrub

In Northeast of Mexico, a large extension of area is found occupied by scrub (approximately 200,000 km^2), which is an association of 60–80 species, known for its low height, distributed in the states of Coahuila, Nuevo Leon, and Tamaulipas (Udvary 1975). There exist a large number of scrubs with diverse composition and structure. Among the names which have been largely utilized are xerophytic scrubs (dry), cardonals, tetecheras, izotals, nopales, thorn scrub, scrub without spines, *parvifolia* (small leaves), magues, lechuguilla, guapillal, and chaparrals (INEGI 2005). In order to contribute more precise knowledge of this vegetation, García (1999) evaluated ecologically the submontane scrub areas with pristine vegetation in Linares municipality, through the characterization of the sites, based on their composition and structure.

The Tamaulipan thorn scrub is a dominant community in coastal plain of Mexico and is present in Northeast of Mexico, in the states of Coahuila, Nuevo León y Tamaulipas, as well as in south of Texas. According to Muller (1947), the Tamaulipan thorn scrub is an ecological system of great floristic diversity, with spinous species in high lands. According to Heiseke (1984), this ecosystem consists of a great source of forages where the pastures have been practiced in extensive forms since 350 years.

Jurado and Reid (1989) have described the composition and structure of Tamaulipan thorn scrub in Northeast Mexico and evaluated the importance of edaphic, topographic, and anthropogenic factors on the distribution of the plant species; they registered the presence of 51 species, mainly shrubs and succulents; the vegetation has an average height of 4 m, distinguishing three strata in the same. The analysis of association showed that the 37% distribution of species is associated with one or more of the environmental factors considered.

Foroughbakhch and Heiseke (1990) mentioned that from the viewpoint of productivity and under the current schemes of exploitation, scrub presents very low productivity, which constitutes the main cause of its degradation and destruction in favor of agricultural land and artificial prairies. They carried out a study about the application of silvicultural management methods and techniques in the scrubland in order to increase forest and livestock production, managing techniques such as thinning, enrichment, and controlled regeneration in an area of Tamaulipan scrub in Linares, N.L.

Reíd et al. (1990) studied structural and floristic variation in Tamaulipan thorn scrub in Northeast Mexico and concluded that the regional variations in climate, substrate, and topography are responsible for the main differences in vegetation and also found evidences that the changes of vegetation are caused by overexploitation of pastures and also selective cutting of timber-yielding species or combustibles.

Carrillo (1991) undertook a study in an area of Tamaulipan thorn scrub at Linares, N.L., with an objective to determine and compare the effects of some silvicultural treatments and also the abiotic factors on the regeneration of scrub, in order to obtain evidences which permit to implement a management program for increasing the productivity of scrub. The silvicultural practices utilized were (1) flush cutting, (2) flush cutting with plantation (introduced species), (3) thinning of 20% and plantation, (4) thinning of 40% and plantation, and (5) thinning of 60% and plantation. It was found that frost affects the scrubland evenly regardless of the thinning treatment carried out, but the thinning practice affects the recovery speed of the plants, with 60% thinning showing the best recovery.

Rodríguez (1994) undertook a study on phytodiversity of two communities of Tamaulipan thorn scrub (disturbed and non-disturbed) at Linares, N. L., and reported that the non-disturbed community (high scrub) presents characteristics with greater diversity in species level and greater complexity in structure, while the disturbed community (low scrub) was found with previous successional state but lower complexity in structure.

Medina (1995) evaluated the effect of fragmentation of natural vegetation on the Tamaulipan thorn scrub biodiversity at Linares, N.L. He did not detect the effect of size of fragmentation in relation with phytodiversity. However, the author argues that the similarity in the phytodiversity is due to the recent fragmentation; in addition to that, the sampling was performed in the center of the fragments, and it is possible that the conditions of decline in the diversity are not yet present in that zone.

Rocha Domínguez (1995) undertook a study in a community of Tamaulipan thorn scrub with an objective to determine the presence of nodricism for *Astrophytum asterias*. The author determined some ecological parameters (abundance, dominance, importance value, etc.) for this community, reporting *Opuntia leptocaulis* as the most abundant species (46.9%), *Prosopis laevigata* as the species of greater dominance (24.1%), and higher frequency (66.7%). With respect to the importance value, *O. leptocaulis* presented a value of 32.5%, followed by *P. laevigata* with 24.2% and *Acacia rigidula* with 20.7%. On the other hand, a global canopy cover of 80%, being the middle stratum (1.5–3 m), and the greater individual cover of 57.5% are reported for that scrub. It was determined a 30% of soil with cover of organic matter and 70% of soil without cover of organic matter.

Despite all the above information, Yerena-Yamallel et al. (2011) recommend studies on the species of Tamaulipan thorn scrub, to elaborate the methodologies for measurement and make an inventory of the variables such as carbon content of these species in order to provide future alternatives for generating economic resources for the residents of Northeast Mexico.

4.2 Botanical Description of the Species Selected for the Study

To fulfill the objectives of the study, only five species from Tamaulipan thorn scrub were selected for greater economic importance with special reference to timber yielding and ecological importance (Alanís et al. 2008; Jiménez et al. 2009). The description is based according to literature of Vines (1984) and Everitt and Lynn (1993).

4.2.1 *Helietta parvifolia* (Gray) Benth. (Rutaceae). "Barreta"

Shrub or tree, from 3 to 5 m height, branches thin without spine. Leaves opposite, trifoliate, and generally oblong-obovate with the entire margin, and leaflets usually oblong-obovate with entire margin. Small flowers, white in color. Fruit samara, trilobed with 3–4 partitions, trialed. Grows in dry soil, distributed in Nuevo León, Tamaulipas, Coahuila, and Querétaro. The timber is utilized for firewood, posts, horcones in house, and fences of rural habitation and corrals (Fig. 1.1).

4.2.2 *Ebenopsis ebano* (Benth.) Coulter (Fabaceae). "Ebano"

Tree up to 15m in height. Alternate leaves, bipinnate with 1–3 pairs of pinnae, 3–6 pairs of leaflets in each pinna of elliptic form, oval or ovate. Fruit a legume of coffee black with numerous seeds. Found on soil with calcareous matters with one layer of clay, distributed in the states of Tamaulipas, Nuevo León and Baja California. Timber is used in the region for firewood, posts, boundary of houses, and elaboration of carts (Fig. 1.2).

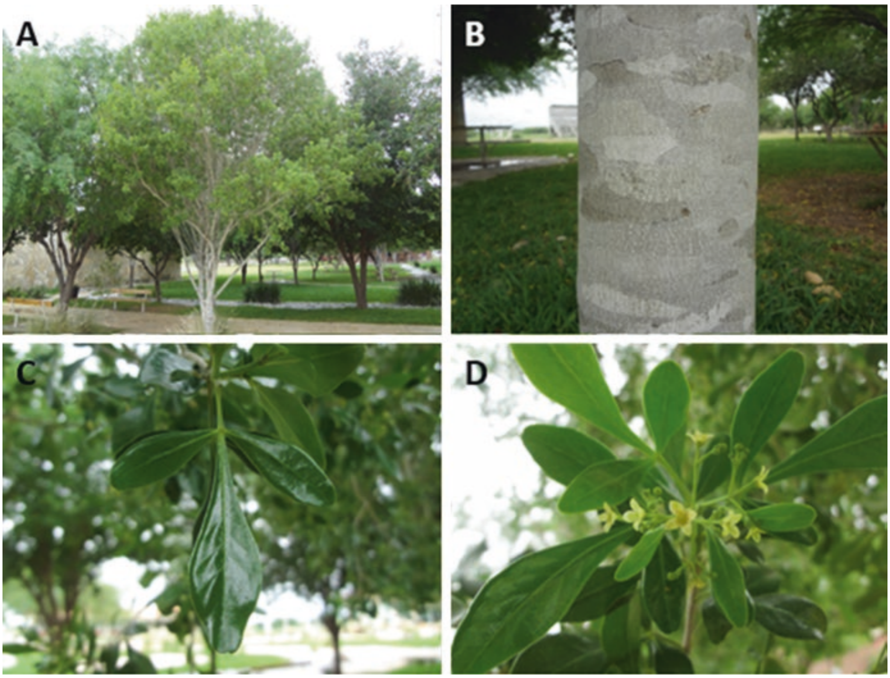


Fig. 1.1 Morphological characteristics of *Helietta parvifolia* "barreta." (**a**) Canopy, (**b**) trunk, (**c**) leaves, (**d**) inflorescence

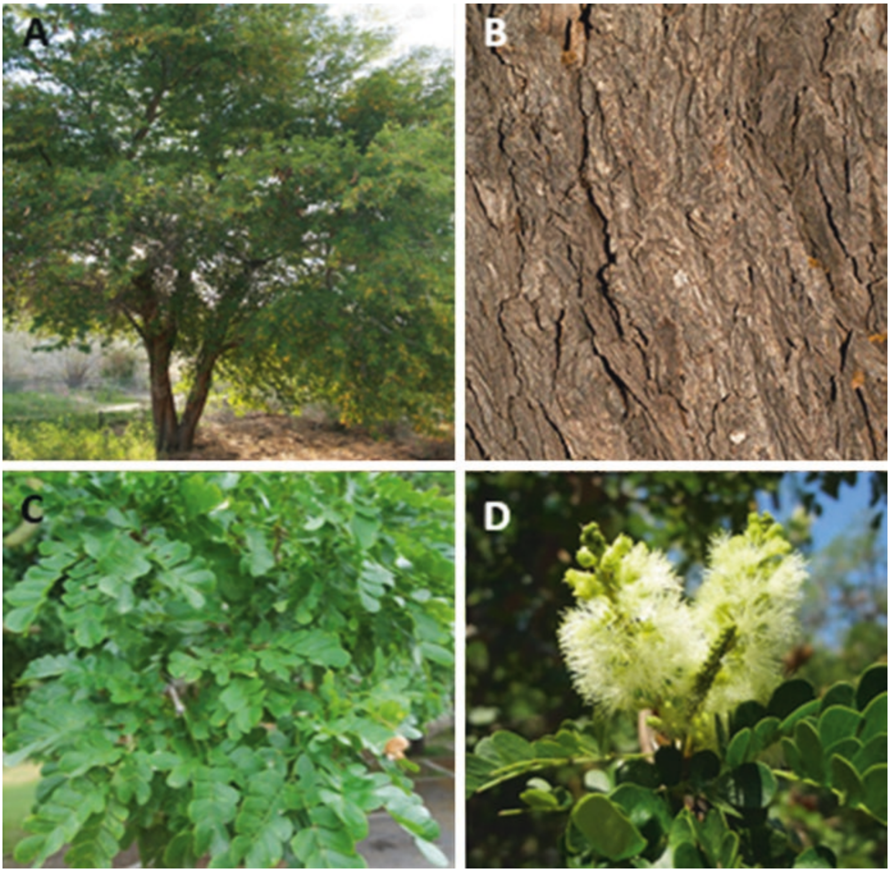


Fig. 1.2 Morphological characteristics of *Ebenopsis ebano*, "Ebano." (**a**) Canopy, (**b**) bark, (**c**) leaves, (**d**) inflorescence

4.2.3 *Havardia pallens* (Benth.) Standl. (Fabaceae)."Tenaza"

Tree spiny usually 1–2 m in height, rarely reach 6 m. Leaves bipinnate with 3–6 pairs of pinnae and 7–20 pairs of leaflets per pinna, of oblong in form. Flowers white. Fruit a legume of coffee reddish in color with numerous seeds. Usually is localized in alluvial soils in the states of Nuevo León, Tamaulipas, Coahuila, and San Luis Potosí. The timber is utilized in the region for firewood, roofs, elaboration of dolls, furniture, and staircase (Fig. 1.3).

4.2.4 *Acacia wrightii* Benth. (Fabaceae). "Uña de gato"

Shrub spinous or tree small of 2–3 m in height, with branches extending to form irregular canopy. Leaves solitary or in fascicles, bipinnate with 1–3 pairs of pinnae and 2–6 pairs of leaflets per pinna, of obovate or narrow oblong in form. Flowers in

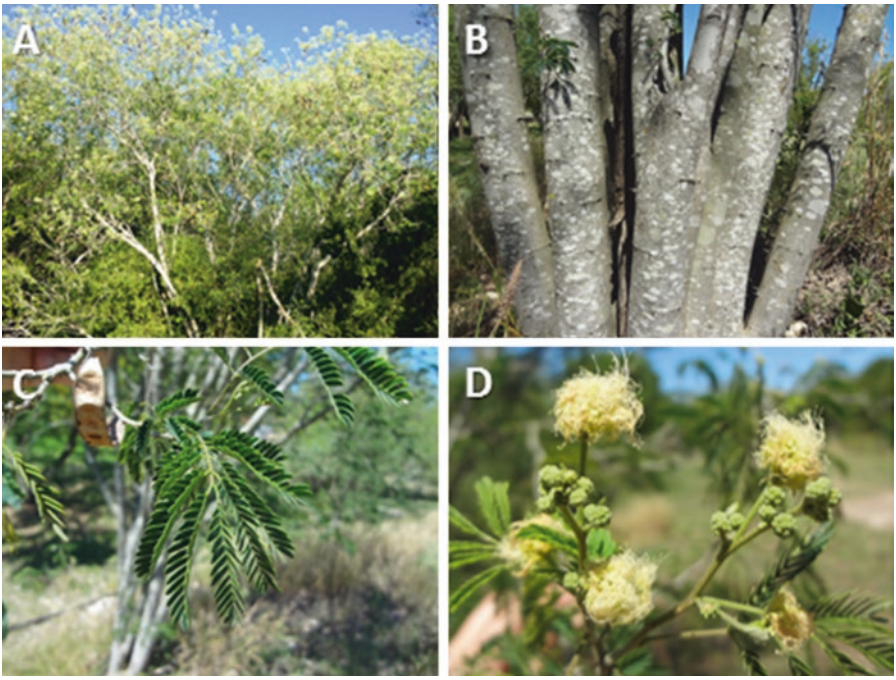


Fig. 1.3 Morphological characteristics of *Havardia pallens*, "Tenaza." (**a**) Canopy, (**b**) trunk (**c**) leaves, (**d**) inflorescence

white color. Fruit a legume, wide of clear coffee in color. Grows in dry stony, localized in the states of Sonora, Tamaulipas, and Nuevo León. The spikes are utilized by bees for the production of honey; the timber is utilized in the region for firewood, posts, fences in the house, and fabrication of furnitures (Fig. 1.4).

4.2.5 *Acacia berlandieri* Benth. (Fabaceae). "Huajillo"

Shrub of origin America and Northeast Mexico. Reach the height of 1–5 m, flowers spherical of white color, flower during February and April (Fig. 1.5). Contains wide variety of alkaloids and may cause toxic effects to domestic animals (Clement et al. 1997). Contains derivatives of dimethyl tryptamine and cyanogenic glucosides in the leaves, seeds, and bark might be risky for health in particular due to the presence of cyanogenic glucosides in leaves, seeds, and barks; the ingestion of these might be risky for healthy (EFSA 2012). Toxic for cattle and must be utilized as forage.

Fig. 1.4 Morphological characteristics of *Acacia wrightii*, “Uña de gato.” (**a**) Canopy, (**b**) spines in branches, (**c**) leaves, (**d**) inflorescence

4.3 Phenology

The study of natural periodic event involved in life cycle of a plant is called phenology (Volpe 1992; Villalpando and Ruiz 1993; Schwartz 1999), with the word deriving from Greek *phaino* which signifies manifest and *logos* as treated. Fournier and Charpantier (1978) mentioned that it is the study of biological phenomenon accommodated to certain periodic rhythm such as initiation of buds, maturity of fruits, and others. Phenology signifies the different phases of the life cycle of the plant starting from seedling emergence, initiation of leaf, flowering, and fruit maturity. As they are natural, these phenomena are related to the climate of the locality in which it occurs and vice versa; phenology can be derived sequences related to the climate and especially to the microclimate when neither one nor the other know each other properly.

This terminology is first used by Belgian botanist Charles Morren in 1958; however, the observations of data on phenological events were used in various cycles before in antique China, where phenological calendars were developed, in centuries before Jesus Christ (Basaure 2009).

Since in more than 200 years, some farmers of the USA started their register of the sowing dates, emergence, foliation, leaf falls, and others, of many plant species. Then with development of thermometer, it was possible to correlate these phases

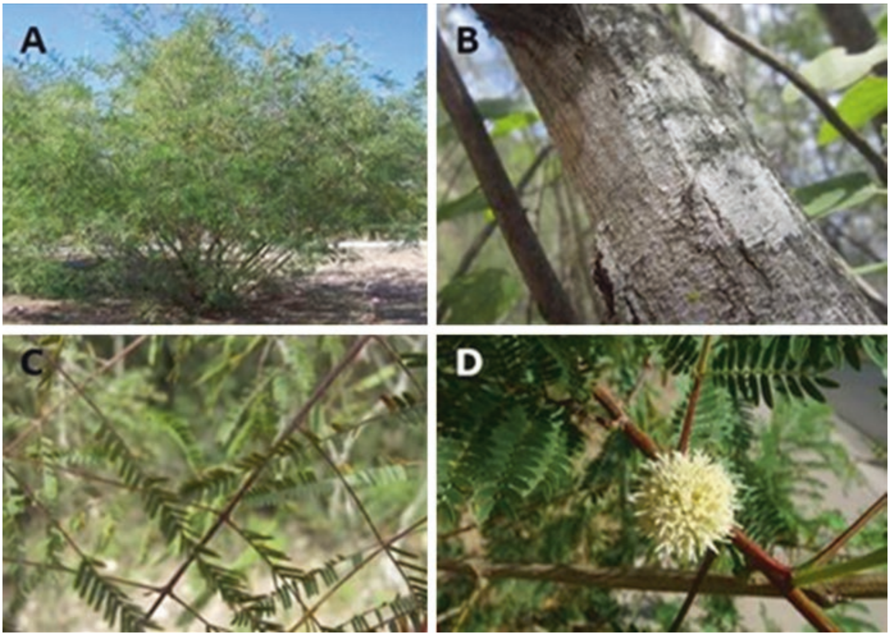


Fig. 1.5 Morphological characteristics of *Acacia berlandieri*, "Huajillo." (**a**) Canopy (**b**) trunk, (**c**) leaves, (**d**) inflorescence

with temperature and humidity. In 1918, Andrew Hopkins established the bioclimatic law, amplified in 1938, where the use of phenological observations is recommended instead of meteorological observations since the former integrate the effects of microclimate and edaphic factors in the life of plants, so that another instrument cannot do.

Actually, sufficient information is available on climatic, edaphic, and biological factors involved in the duration of biological cycles and production of the crops. However, it is frequently used in the terminology days after sowing (DAS) relating it to the observations and practices that are carried out without taking into account the effect of such factors on the morphology of plants (Volpe 1992).

The biological cycle changes with genotype and climatic factors during the cycle which means that the same genotypes sown in different conditions present different stages of development during the same chronological phase. Therefore it is very important to note phenological phases at the time of the crop in particular stage development (Hopkins 1918).

The studies of plant phenology are very important for the analysis and the management of the ecological system. These studies may be useful for planning the program of management and plant recovery and the explanation of the adaptation of the species in the environments (Fresnillo-Fedorenko et al. 1996). In this respect, Yan and Wallace (1998) elaborated a model for plant phenology-based interaction genotype × temperature and photoperiod, showing exit for simulating and predicting phenology of five species of crops, pea, oat, wheat, and maize, the first three of long photoperiod and the rest of short photoperiod. On the other hand, Baumgartner and Hartmann (2000) reported exit result of the phenologic model in the program of plant conservations; these authors elaborated a phenologic model to adequate the date of cutting “narciso” (*Narcissus radiiflorus*), which pretends the conservation of this species in the European Alpine zone, up to the date of cutting done on empiric base; with the development of this model, it was possible to calculate a confident date for the cutting of the plant, thereby assuring the maturity of seeds.

The phenological events of desert plants disparated mainly by the lack of adequate temperature (Beatley 1974 cited by Rossi et al. 1999); in this respect, some authors suggest that the low temperature and high radiation are the important environmental factors for flowering in the humid tropical forest (Rondón 1992). The majority of woody tropical plants produce new leaves and flowers in specific not continuously, and the majority of tropical forests present seasonal variation in the appearance of new leaves, flowers, and fruits; this pattern suggests that the phenologic changes represent biotic and/or abiotic factors, among which the climate is the main factor (Van Schaik et al. 1993).

Cantú-Ayala and Reid (1991) are one of the few first persons reporting knowledge on the phenology of 59 species of Tamaulipan thorn scrub at Linares, N.L. They report that the period of foliage was highly variable among the species. The flowering is concentrated during more hot season of the year particularly in spring and summer; flowering was concentrated in the warmer part of the year, particularly in spring and summer. With respect to the types of fruits, it is found that the legumes are more common (31%), as well as drupes (28%) and capsules (15%), and the rests are berries, achenes, follicles, samaras, etc. With respect to dispersion, birds are main dispersers (43%).

The knowledge on phenology of crops under drought was better understood. For example, Desclaux and Roumet (1996) mentioned that the drought stress modifies the plant phenology and affects the harvest components of crops. In order to confirm it, a study was undertaken on cultivars of soybean (*Glycine max*), which was submitted to water stress during different developmental stages. The results reveal that drought stress apparently disparated the change of vegetative to reproductive phases. At the same time, the formation of vegetative nodes which appeared before the application of stress was delayed and also flowering and fructification leading to lower production of dry matter in the fruits.

The reproductive phenology is described generally as the period of flowering and fruiting, a relevant factor which determines reproductive productivity of the species which may inhibit the use of seasonal resources, such as light and pollinizers for plants. The time of flowering and fruiting may be important to avoid the production of flowers and seeds (Marco et al. 2000). The reproductive phenology of a tropical forest is characterized by the presence of high diversity within and among forests; this range of variation suggests the great potentials of the phenological studies of tropical forests for the exploration of selective pressures which exercise the biotic and abiotic factors on the plants (Sakai 2001).

In order to study the phenology of communities, Hernández and Carreón-Abud (1987) described the main reproductive phases of trees and some shrubs and herbs of a mesophyll forest and observed the flowing of the trees was highly seasonal reaching its peak during the interphase drought-precipitation, while herbaceous and shrubs flowered basically in humid season.

A great majority of the species of tree species possess high level of autocompatibility which is considered an adaptive mechanism which increases the possibilities of reproductive exit in the absence of efficient pollinizers. Bertiller et al. (1991) cited by Friedel et al. (1994) observed that the appearance of the phenological events of shrubs in the arid zones depends mainly on the depth of root system and availability of moisture and nutrients.

A study was undertaken by Gonzalez-Rodriguez et al. (2015) to determine flowering and fruiting phenology of 12 woody species in Linares, Northeast of Mexico, during the period from March to December 2013. The species included were *Prosopis laevigata* (Humb. and Bonpl ex Willd.). M.C Johnst., *Ebenopsis ebano* (Berland.) Barneby and J.W Grimes, *Acacia amentacea* D.C., *Castela erecta* Turpin sub sp. texana (Torr. and A. Gray) Cronquist, *Celtis pallida* Torr., *Parkinsonia texana* var. *macra* (IM Johnst.) Isely, *Forestiera angustifolia* Torr., *Cordia boissieri* A.DC., *Leucophyllum frutescens* (Berland.) IM Johnst., *Guaiacum angustifolium* Engelm., *Cylindropuntia leptocaulis* (DC.) F.M Knuth, *Opuntia* spp., *Zanthoxylum fagara* Sarg., *Sideroxylon celastrinum* (Kunth) T.D. Penn, and *Helietta parvifolia* (A. Gray ex Hemsl) Benth., among others. There is a large variability in the phenological stages among species. The first study was concentrated on the basis of the percentage of different phenological stages. The second study was mainly concentrated on the time of appearance of each phenological stage in individual species. The results reveal about the variation in phenological time schedule among different species. Very little studies have been undertaken in this aspect in the literature. Therefore, there is a need to evaluate the phenology of each individual species. This knowledge will help forest managers for efficient management of the forest as well as the time of seed production of the species.

4.4 Biomass

According to Odum (1965), the biomass may be defined as the production of dry matter per unit of surface. Approximately 90% of the biomass accumulated in the Earth is found in the forests in the form of trunks, branches, leaves, roots, and organic matter (Raev et al. 1997; Leith and Whithacker 1975).

The biomass (on the basis of dry mass) of trees can be measured by cutting the tree and dividing it into different components (wood of different sizes, leaves, fruits, etc.), weighing fresh and dry weight of each sample for determining moisture content (Stewart et al. 1992). This quantification of production by the measurement of weight is a direct form and more adequate for expressing the productivity of biomass of a species (Salazar 1989). Generally, the biomass is measured in different components and consequently exists less additive processing (Cunia and Briggs 1984; Parresol 1999). The additive values consist of the sum of each of the components.

The biomass has other aspects such as positive incidence in the prevention of forest fire and improves the condition of forests, maintenance of plant population, and employment in rural environment (Alvares-Vergel et al. 2011).

The methods for the estimation of biomass potential of forest are various, but its precision decreases with an increase of the extension of field to evaluate, being very difficult to replicate the results in other zones owing to the facts that the changes in climatic and edaphic phenology are highly variable. The changes present in the production of biomass and diversity in the gradients of productivity are controversial in places where the study has been realized for determining these relations in terrestrial ecosystem.

The capacity of the production of biomass to a large scale is of 40 million tons per year of which the partition of solid biomass is of 40–50% (Wu et al. 2011). According to PNUMA (2010), the biomass in its different forms is an important energy source for more than two millions of years. In Mexico, so far there are no confident estimations of the quantity of residues present during the exploitation of forest, in similar conditions as is found in the estimation of the residues of industrialization of forest products.

In plants during the process of photosynthesis, solar energy is stored in the plant biomass, which helps in the transformation of carbon dioxide (CO_2) of the air and water from the soil to carbohydrate (Enciso 2007). This energy may be utilized in various forms, and the biomass is then converted to combustibles. Since in the long time, the biomass is being used as a combustible fuel.

Since in remote times, while our primitive men lived in caves in the primitive period of age, man learnt to manage fire (Antal and Gronli 2003). Later during the course of time in Egypt, the system of the production of woody biomass was perfected, and the progressive use of plant carbon constituted the basic energy of antique civilizations (Patiño and Smith 2008). Later on with the industrial progress, the function of metals and the use of internal combustion motor diminished subsequently, and it was substituted by mineral carbon and petrol (Martín 1989). Actually in some countries, the biomass is the main source of energy, and in world level, it is considered as a modern and clean way to obtain energy (Patiño and Smith 2008).

Some benefits attributed to the use of biomass as energy source are energy security and prevention of different sources decentralized, may help the nations to reduce dependence on fossil fuels, promote rural economic growth, stimulate the growth of agriculture, and favor the protection of environment by the compensation of the use of fossil combustibles and low emissions of nitrogen oxide, sulfur dioxide, and other contaminants (Carrillo-Parra et al. 2015).

However, from the benefits of the use of biomass as energy source, the biomass in original form presents some inconveniences such as high moisture content (>50%), great diversity in form and irregular size (<0.2 mm and 30 mm), and low density (40–400 kg m^{-3}), which reduce quality energy. Further its management, transport, and storage are also difficult (Kaliyan and Vance-Morey 2009).

4.5 Litterfall

Since Bray and Gorham (1964) presented the evidence of the importance of the leaf fall litter, researchers in various countries of the world have focused on this theme. However, the term has taken different focusses; for example, Proctor et al. (1983) in England designate "litterfall" a mixture of materials such as leaves, branches, fruits, inflorescences, and unidentified structure, deposited by trees and shrubs in the forest. Pérez et al. (2006) in Argentina used the term "mulch fall" and referred to fall of needles, branches <1 cm, and miscellaneous. In Mexico, Návar and Jurado (2009) defined the term "foliar productivity" as the organic matter deposited on the soil (foliage, branches, trunks, etc.). China (Liu et al. 2001; Guo et al. 2004), Grecia (Kavvadias et al. 2001), Japón (Xu and Hirata 2002), Colombia (Zapata et al. 2007), and Mexico (Pavón et al. 2005; González et al. 2008; Nájera and Hernández 2009) adapted the proposal Anglo-Saxons "litterfall," for which the present consider to use the term "fall or accumulation of leaves," owing to the wide use in Mexico and different parts of the world. It is considered as mixture of all organic residues of the plants which fall on soil like leaves, branches <2 cm, fruits, and inflorescence and miscellaneous (Proctor et al. 1983; González et al. 2008). The litterfall is of great importance especially where the vegetation depends on nutrient cycle derived from the deposition of this (Bernhard-Reversat et al. 2001).

Spain (1984) announced that litterfall in the forests is associated with the transfer of energy and nutrients from their biological components on soil surface and initial point for nutrient cycle. The accumulation of organic matter produced by litterfall and their decomposition is an important factor for the formation of soil such as the process of nutrient cycle (Van Wesemael 1993). The litterfall is an important factor of nutrients of forest soil (Vitousek and Sanford 1986; Landsberg and Gower 1997) and represents ~80% of total nutrients returnable in the soil by parts of trees (Santa Regina et al. 2001). The quantity and nature of litterfall have important relation with the formation of soil and the maintenance of its fertility, so the quantification of its production and nature is important for the composition and nutrient cycle (Rai and Proctor 1986). Litterfall is related to the productivity of tree, its phenology, and the rates of renovation of biomass (Williams and Tolome 1996).

4.6 Forest Plantation

Forest plantations are defined as those formations of forest established in the context of forestation or reforestation process (García-Mosqueda et al. 2014). The increasing social demands of the products and services require enormous force for the establishment of new forests where appropriate intensive forest management of plantations may supply the local and global markets of timbers, thereby contributing in a significant manner rural and industrial development. According to the information of world evaluation about forest resources 2010 (FAO 2013), between 2000 and 2010, the forest area planted increased to five million ton hectares per year, established in majority through forestations (it means the tree plantation in the soils is classified as forest), especially in China.

On the other hand, the plantation favors the forest sector and helps in the decrease of the pressure and use of thorn scrub forest and also the exploitation of areas altered by agricultural activities or animal husbandry (INE 2007). From technical perspectives, the combination of knowledge of silviculture, economic and social ecology, and finance is a sufficient argument to hypothesize that in Mexico the plantation of forests constitutes viable option with the possibilities to adopting measures for the economic development of the country (Zamudio Sánchez et al. 2010). With this motive, it is convenient to count the reliable instruments for the evolution and monitoring of wild populations and their association, so that its characterization serves as a base for the elaboration of adequate management plans or modifies the actual practices of exploitation tending to the conservation, improvement, and sustainable use of ecosystem in arid and semiarid zones (Meza 2002). In the equal manner, the evaluation of plantation may provide sufficient information for the development of this instrument.

4.6.1 Silviculture and Process of Logging

Etymologically the word silviculture signifies "the crop of the forest." Although the origin of silviculture is considered as an art, at present it is also considered as science which studies the techniques through which is created and conserved not only the forests but also the forest mass, exploiting a continuous mode with greater possible utility and thereby taking special care in their regeneration, which may either be natural or artificial (Santillán 1986). From the practical point of view, the silviculture implicates the manipulation of forest mass with an objective to obtain the desired forest (such as timber, firewoods, fruits, barks, etc.) and offer indirect benefits (such as avoiding or correcting soil erosion or regulating the lake and "the flow of the springs," preventing the formation of alludes, fixing the movement of sands, regulating microclimate, conditioning the places of spacing, and improving the soil quality) and at the same time to achieve the permanence and renovation, considering obviously biologic, ecologic, dasonomic, economic, and social criteria (Santillán 1986).

In this way, the silviculture is understood as the care of the forests, its orientation to obtain the maximum productivity, by sustaining its resources and benefits. For example, Campos (2009) indicates the different methods employed in the logging of trees for obtaining wood to a sustainable development. It is recommended to conduct this practice in autumn or beginning of winter, so that in this approach, the flow of the vascular juice has ceased as in other parts of the year. If the wood has sufficient quantity of vascular juice, it may provoke the proliferation of insects attacking the wood.

Besides the gestion, silviculture may maintain the tree mass in good condition so that the trees do not suffer deformations in their trunks and retain the properties of wood. For this, there are two operations pruning of the branches with the objective that the total energy of the tree is destined to generate wood in the trunk or in thickening and the logging of tree of large size expected for the description of logs by trees sown (Campos 2009).

4.6.2 Wood as Prime Matter

Once cut, the tree supplies wood which is applied in the industries of construction, furnitures, and many objects (Ortuño 1998). Always the principles of natural resources helped the mankind and thanks to the technological progress assisting to serve many uses. The chemical industry is extensively utilized the wood for reasons of its physical and mechanical properties to obtain many products of great values (Campos-Cisneros 2007). With the difference of a greater part of basic matters, the wood is a renewable resource, if well administered; otherwise it may convert to an ecological disaster. In this way, it is proposed the forest mass is a source of energy. Biomass may be virtues or wood chips, the products of forest cleanings or even of their rational exploitation. To use wood in the chemical industry in the most efficient way, it is necessary to know the different substances that constitute it.

4.6.2.1 Wood Components

All the plants and especially woody species are constituted in majority of the components, C, H, O, and N, and also contain small quantities of Ca, K, and Mg. The elements C, H, and O are combined to form organic components of wood, cellulose, hemicellulose, and lignin, as well as pectins (Ortuño 1998).

In describing the chemical components of wood, components of the cell wall and foreign matter are often distinguished. The components of cell wall are lignin and the polysaccharides constituted by cellulose and hemicellulose as Campos-Cisneros (2007) stated (Fig. 1.6).

Cellulose (Fig. 1.7) is the main constituent of the cell wall of all upper plants and the major component of all wood fibers (40–45%). This is constituted by β-D-glucose in the form of pyranose linked together by 1–4 glycosidic bonds with formation of cellobiose residues.

The hemicellulose is found in the cell wall associated with cellulose. This is formed by pentose and hexose distinct from glucose (mannose, xylose, glucose, galactose, and arabinose), linked together with a polymerization grade from 100 to 200. The chemical structure and composition vary according to species. Similarly, all the hemicelluloses are insoluble in H_2O, but can be dissolved in strong alkalis and easily hydrolyzed by acids. Its amorphic structure and low molecular weight confer greater solubility and susceptibility to hydrolysis than cellulose (Ortuño 1998).

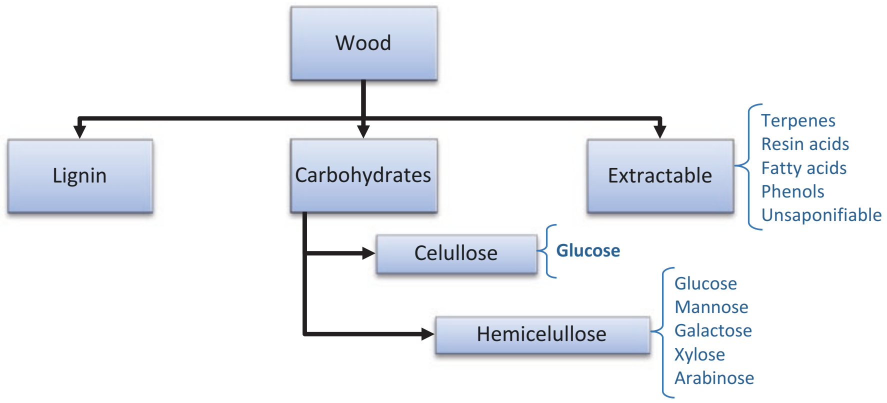
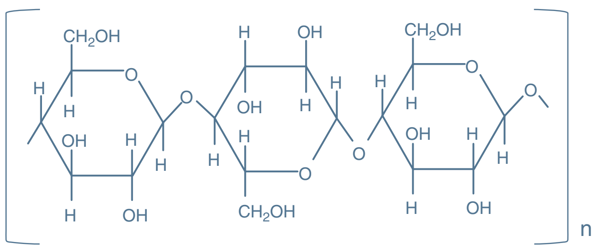


Fig. 1.6 Main components of wood

Fig. 1.7 Chemical structure of cellulose



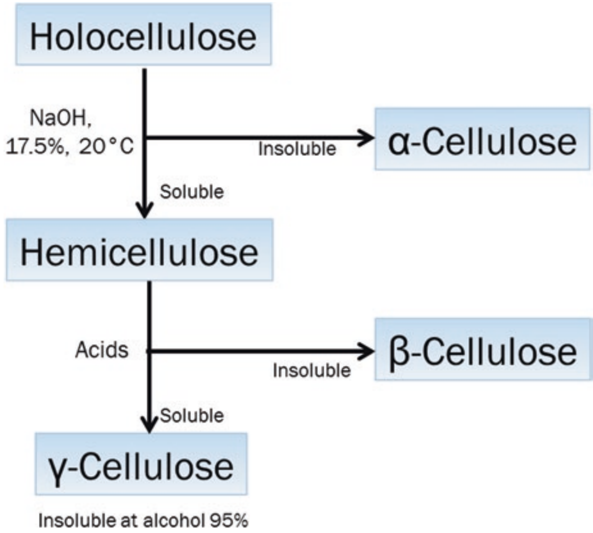
The cellulosic fraction – cellulose and hemicellulose – of wood may be separated in its components, depending on its solubility in NaOH at 17.5%, according to their grade of polymerization (Fig. 1.8), as stated by Ortuño (1998).

The pectins or pectic substances are also hydrates of carbon and form cell wall of young cells produced by cambium, but its contents decrease in old trees.

The lignin is the third component in order of importance of cell wall (20–30%). It is cemented in the cell wall of wood, confers rigidity of the same, and acts as obstacle against the degradation of enzymes of the cell wall. The lignin differentiates the wood from other cellulosic materials. In wood, it is always associated with cellulose, but does not occur the same in other cellulosic materials, so that the cellulose may be found practically in pure condition, for example, in cotton (Ortuño 1998).

Lignin is a tridimensional aromatic polymer in which phenylpropene units are repeated with different types of bonds (ether or C–C) between the monomers. This gives a complex structure which may be solely defined by the frequency with what appear determined unions. It is difficult to separate lignin of wood, besides it alters with the method of extraction. The molecular weight of the separated product may vary between 1000 and 20,000 g/mol (Lu and John 2010).

Fig. 1.8 Scheme of separation of the wood cellulosic fraction



Owing to the high content of these aromatic and phenolic compounds, the lignins present dark color and are easily oxidized and are relatively stable in aqueous acidic minerals, but are soluble in aqueous bases and hot bisulfite.

The wood also contains a series of compounds called extracts of varied chemical composition such as gums, resins, fats, alkaloids, and also tannins, which can be extracted from wood by cold or hot water or organic solvents such as alcohol, benzene, acetone, or ether. The proportion of these substances is among 1–10%, although some tropical species may contain up to 20% of the same. The inorganic compounds are not soluble in the mentioned solvents, but sometimes are included among the extracts (Ortuño 1998).

The extraneous matters are constituted by substances which can be separated by extraction by nonreactive dissolvents, protein residues of the protoplasm of the growing cell, and mineral components; some of them are very difficult to remove.

4.7 *Bioenergy and Biofuels in Mexico*

Bioenergy is defined as the manner to generate energy from biomass, "living matter" or "derived from living matter," including a wide range of products which are divided into three types of fuels – the solids (firewoods, charcoal, agricultural and animal residues, and municipal wastes) which are gasified to produce heat and electricity and liquid fuels of the wood, which are utilized in energetic crops (sugarcane, oil seed, palm, coconut, and castor oil) to generate ethanol and biodiesel (Masera Cerutti et al. 2006). This was the first source of energy known to mankind. Wood and even dry excrement are biofuels.

Masera Cerutti et al. (2006) described the different bioenergetic resources in Mexico, analyzing the actual existences of resources, and explored the technical potential of forest resources. They also presented the applications of technologies through revision of the main technologies available for exploitation of bioenergetic resources. Besides the sceneries of medium- and long-term technologies for the substitution of fossil fuels by biofuels, it should be noted that in the theoretical notebook "Advanced Biofuels in Mexico" (Sandoval 2010), mention is made of advanced biofuels (ethanol, fuel, Green Diesel, and biodiesel), making reference in studies and projects on this type of biofuels.

By biofuels, it means that fuel of biological origin has not been fossilized. If no "fossilized" is added, oil, mineral coal, and natural gas would be considered biofuels, because their origin is also biological, but they have been fossilized hundreds of thousands of years ago (Camps and Marcos 2008). The use of biofuels in the country is in the process of development. However, Mexico produces ethanol for use as alcoholic wine, pharmaceutical products, and food as solvent and industrial reactive. The ethanol actually produced comes from the juice of sugarcane and is obtained in some sugar mills, through the fermentation of the juice and the distillation (Álvarez-Maciel 2009).

According to BNDES and CGEE (2008), there is a strong transition from uses involving "low technological level" (such as firewood for cooking) to more advanced commercial uses (electric power, steam, fuel).

4.8 Factors Influencing the Quality of Biofuel

The concepts of quality depend on granulation, moisture content, ash, and fixed carbon, as per satisfaction of the consumer and also of the specific wood utilized (Camps and Marcos 2008). The term immediate analysis is utilized for standard tests to indicate standard tests in order to determine the quality of combustible (Ndudi and Gbabo 2015), based on the determination of moisture content, volatile material, ash content, and fixed carbon (ASTM 1995). The main characteristics which define the quality may also consider density and calorific value (Pérez and Compean 1989). While all of these properties are in some way interrelated, they are measured and valued separately.

In order to obtain a biofuel, the main processing steps for the treatment of residual biomass are fragmentation, drying, and compaction, with the aim of facilitating the ignition and combustion of the biofuel, increasing its calorific value by reducing its humidity, and increasing the density and storage costs by decreasing its volume. The chemical transformations depend on the properties that contain the material as its calorific value, the quantity and composition of ashes, and chemical composition as these properties affect the combustion as well as the design and performance of the combustion systems (Martín 2001).

4.8.1 Moisture Content

The wood is a hygroscopic material that always contains water, and in fact in the standing tree, the function of the wood is the transport of water from the root to the leaves, allowing the process of growth (SENA 1987). For adequate use of wood, once the tree is cut, it is necessary to remove water to dry up to a moisture content, which depends on the conditions of later use of the wood.

The term moisture content (MC) is defined as the "amount of water a piece of wood contains, expressed as a percentage of the anhydrous or dry weight of the wood. The formula for calculating the moisture content is presented in Eq. 1.1:

$$MC(\%) = \left(\frac{Wo - Wd}{Wd} \right) \times 100 \tag{1.1}$$

where Wo is the original weight and Wd the dry weight in oven.

The moisture content has effect on the duration of the combustible in store without any deterioration by the attack of fungus and other microorganisms, thereby affecting net caloric power, efficiency of the combustion, and energy production and its durability (García et al. 2012; Obernberger and Thek 2004).

4.8.2 Volatile Materials

The volatility in the context of chemistry, physics, and thermodynamics is a measure of the tendency of one substance to a substance to produce vapor subjected to a greater vapor pressure. It is also defined as a measure of the factibility of a substance to evaporate. At a temperature given to a substance with high vapor pressure, it evaporates easily than one substance with lower vapor pressure. The volatile material is the quantity of biomass liberated when it is heated at a temperature ranging from 400 to 500 °C (Kaliyan and Vance-Morey 2009).

4.8.3 Ash

The percentage of a noncombustible material indicates per kilogram of the material, being a key parameter for causing problems in combustion boilers. This includes (1) the observation of fan in the grill; (2) the automatic system of cleaning of the burners and the interchanger which may be damaged; (3) generating more products, not burnt which need to be removed frequently; (4) automatism, probes, etc. which may be damaged; (5) the condensed tars in chimneys which may affect the electric fans in liberation of fumes (Ortiz Torres 2006; Vega-Nieva et al. 2014b).

4.8.4 Fixed Carbon

The pure carbon which contains one solid fuel, according to Márquez (2009), is an energetic component of greater importance which constitutes a crystalline structure where the chemical bonds prevail in carbon atoms. In metalary the fixed carbon is a very important component which is for the reduction of the oxides of iron during the production of melted iron.

4.8.5 Calorific Value

The calorific value is understood as the quantity of energy available per 1 kg of fuel after burning. This is the fundamental characteristic that defines a fuel and as such depends basically on its chemical composition (Ortiz-Torres 2006). The calorific value can be determined by calculations from the content of the different elements constituting the fuel, as can also be determined experimentally by the use of a calorimeter, which measures the exact value of the heat released during the combustion process of the material to be analyzed.

4.9 Classification of Biofuels

Depending on the process of obtaining biofuels and their physical properties, they are classified as solids, liquids, and gases (Dragone et al. 2010). The liquid biofuels are obtained through chemical process from vegetable oils and animal fats or crops with sugar content, while the gaseous biofuels are obtained from decomposition of organic matter in the absence of air. As for solid biofuels, they are produced by physical processes for the generation of energy and are mostly used in heating systems. There exists a large variety of solid biofuels; the types mostly utilized in the heating systems are firewood, wood chips, pellets, briquets, and agroindustrial residues such as olive bone, almond husk, grape pruning, etc. (IAASTD 2009). These different types of solid biofuels till date have been derived from forest biomass and are presented in Table 1.1, and consequently each of these is described on the basis of available studies mentioned before.

Table 1.1 Solid biofuels derived from forest biomass

Biofuel	Particle size	Method of preparation
Briquets	$\Phi > 25$ mm	Compression
Pellets	$\Phi < 25$ mm	Compression
Chips	5–100 mm	Sharp tools

Table 1.2 Composition of the main elements of the wood biomass types

Wood biomass	% on wet basis					
	Moisture	Ash	Volatiles	Sulfur	CV (kcal/kg)	Density (kg/m^3)
Chip	20–55	1–2	>65	<0.05	1.600–3.300	250
Sawdust	20–55	<1	>65	<0.05	1.600–3.300	350
Pellets	<12	<1	>65	<0.05	>4.000	650
Briquets	<10	<0.7	–	–	>4.400	580
Firewood	20–30	1.2	n.d.	0.02	3.000–3.400	380

CV Calorific value

Table 1.3 Charcoal quality standards according to physicochemical characteristics by market

Market	Norm	Chemical purity			
		Fixed carbon (%)	Volatiles (%)	Ash (%)	Moisture (%)
Belgium	NBN M11-001	75	12	–	7.0
France	NF N° 846 E	75	12	–	7.0
Germany	DIN 51749	78	16	6	8.0
Russia	GOST 7657-84	77	14	3	6.0
USA	DIN EN 1860-2	75	9	8	8.0
Japan	–	76	12	4	7.5

Table 1.4 Charcoal quality standards according to granulometry by market

Market	Norm	Chemical purity		
		>20 mm (%)	>10 mm ≤20 mm (%)	≤10 mm (%)
Belgium	NBN M11-001	75	19	6
France	NF N° 846 E	19	19	–
Germany	DIN 51749	6	–	–
Russia	GOST 7657-84	77	14	3
USA	DIN EN 1860-2	20	10	–

4.9.1 Norms of Charcoal Quality

The charcoal is a product obtained from carbonization of wood under controlled condition in a carbon oven; during this process, the entry of air is restricted. This does not occur in conventional fire, but this is exposed chemically for the formation of charcoal; it is a solid product and fragile and porous with a high content of carbon (80%). It is produced by heating the wood in the absence of air (up to temperature of 400–700 °C). The capacity of the production of heat of charcoal is greater than that of original wood (Goche-Télles et al. 2015).

Table 1.2 presents the principal elements composing the different types of solid fuels, with some characteristics according to Sánchez (2012) and Estévez (2014).

The European and Asian markets regulate charcoal quality with norms based on physicochemical characteristics (Table 1.3), color, sound, facility to ignite, taste, and granulometry (Table 1.4). On the other hand, in the USA, the quality based on granulation should avoid the production of sparks and presence of dusts and impurities (Stassen 2002).

The other characteristics which should be considered are basic density and the volume of the solid, so that these may be defined as the mass of combustible wood, important for the determination of energy quality per unit volume (Enciso 2007).

In Mexico, despite the importance of charcoal production at national level, there is deficiency of standards, practices, and adequate norms to determine the relation yield quality and classification of products. Charcoal quality is determined on the basis of empirical knowledge related mainly to the satisfaction of consumers, who identify it according to the presentation, in bulk or packed, with or without mark (Arias et al. 2010). On the other hand, García (2010) indicates that the quality is classified by metallic sound, color, tone, and robust size with dimensions more than 5 cm and cleaning of impurities such as stones, soils, or whatever other materials.

4.9.2 Environmental Impact of the Forest Sector

The analysis of the environmental impact generated by forestry is performed considering both air and water emissions. In relation to air emissions, the generally inventoried incorporated pollutants include MP10 (material particle of diameter lower or equal to 10 μm), carbon monoxide (CO), nitrogen oxides (NO), organic volatile compound (OVC), sulfur oxide (SOx), and ammonium (NH_3), while the contaminants in water are oils and fats and chloride and sulfate (Madrones and Saavedra 2011).

4.9.2.1 Chloride (Cl^-)

The chlorides are widely distributed in the air, in the form of salts of sodium (NaCl), potassium (KCl), and calcium ($CaCl_2$) (WHO 2003). It is leached from rocks to soil and water by erosion, highly mobile, and transported from basins or oceans. The chloride present in drinking water is derived from natural sources, residual water, industrial derivatives, urban flow contaminated with salt of thaw, and saline intrusions (WHO 2003, 2011; OMS 2006).

The taste of chloride ion in water depends on associated cations, being perceptible in excess of 250 mg L^{-1}. The guide for drinking water does not propose any reference value based on its effects on health for chloride in drinking water but intake of the value of 250 mg L^{-1} (WHO 2011).

The toxicity of Cl^- in humans has not been evidenced, except in the alteration of NaCl metabolism. The consumption of Cl^- for an adult is approximately 1 g per person, per day; for young persons up to 18 years old, a 45 mg day^{-1} Cl^- intake is suggested. The toxicity of the Cl^- would be associated with the united cation (OMS 2006; WHO 2003, 2011).

4.9.2.2 Sulfates (SO_4^{2-})

The SO_4^{2-} is present in natural form in many minerals and is commercially utilized in all chemical industries. They are released to water from industrial waste and by precipitation from the atmosphere. However, the highest concentrations are usually found in groundwater and come from natural sources. In general the average daily SO_4^{2-} intake derived from drinking water, air, and food is approximately 500 mg, being food the principal source. However, in the regions where drinking water contains high SO_4^{2-}concentrations, the drinking water may be the main source of intake (OMS 2006).

The existing data do not allow the determination of SO_4^{2-} concentration in drinking water which is likely to cause adverse health effects. Data from a study in piglets with a liquid diet and studies with tap water in volunteers show a laxative effect with concentrations of 1000–1200 mg L^{-1}, but without increased diarrhea, dehydration, or weight loss (OMS 2006).

Obstinately, none of the value of reference is proposed based on the effects on health for intake of SO_4^{2-}. It is recommended to notify the health authorities about the source of drinking water containing concentration of SO_4^{2-} that exceeds 500 mg L^{-1}. The presence of SO_4^{2-} in drinking water can also produce appreciable taste and contribute to the corrosion of the distribution systems (OMS 2006). The method most employed for analysis of elements is by ionic interchange (Moreno 2011).

4.10 Chromatography

According to the International Union of Pure and Applied Chemistry (IUPAC), chromatography is a physical separation method in which the components to be separated are distributed between a stationary phase and a mobile phase. The stationary phase may be a solid, a gel, or a liquid adhered chemically or immobilized on a solid. The mobile phase constitutes the fluid which penetrates the stationary bed in a given direction and can be liquid, gas, or a supercritical fluid (IUPAC 1995).

The chromatography was invented and denominated by the botanist Michael Tswett in the beginning of the twentieth century, to utilize the technique to separate different plant pigments, which consisted of passing the solution with the contents through a glass column packed with calcium carbonate and finally get separated and divided, which consisted of passing the solution containing them through a glass column packed with finely divided calcium carbonate. The separate species appeared as colored bands on the column, which justifies the Greek name he chose for the chroma method which means "color" and graphein meaning "to write" (Skoog et al. 2008).

4.10.1 History of the Importance of Ionic Chromatography

The ionic chromatography (IC) is applied to whatever modern methods for the chromatographic separation of ions. In the middle of the year 1930, the interchangeable ionic resins were invented and were utilized in the separation of interchangeable ions or anions. Later in 1953 and 1950, the knowledge about the interchange of ions and its applications were amplified by "Manhattan Project" (Metrohm 2010). In the year 1970, the IC revolutionized by demonstrating that the mixtures of cations and anions could be separated in columns by HPLC filled with resins of interchangeable anions and ions, and in 1975, the Dow Chemical Company developed a technique of suppression of eluents making possible the detection of ion eluted by conductivity (Skoog et al. 2008).

The IC may be used in the determination of large proteins, small nucleotides, and amino acids; however, it is dominant in the determination of anions, where its greater field of application is the investigation of aqueous systems, in drinking water (Jackson et al. 2001), for analysis of anionic elements or complex and the third largest field of application is ultra-trace analysis in ultrapure chemical processes required in the semiconductor industry (Eith et al. 2001). The applications may be divided in different segments (Passos 2011):

- Waters: potable, rivers, rain, sea, ultrapure water, industrial effluents, and residual water
- Petrochemicals: organic acids, anions, cations, amines, cyanides, sulfur, phenols
- Drinks: milk, wines, vodka, beer, mineral water, juices
- Food: chocolates, vegetable extracts, mayonnaise
- Pharmaceutical products: micronutrients, hemodialysis solution
- Concentrates: hydrogen peroxide 30%, sodium hydroxide 50%, hydrochloric acid 18 mol L^{-1}
- Organic polar solvent: ethyl alcohol, isopropyl alcohol, acetone, fertilizer, additives
- Paper and cellulose

This interchange should be realized only among ions of the same charge; that means positive with positive and negative with negative. In the cationic interchangeable chromatography, charged cations are retained positively, owing to the fact that the stationary phase is found charged negatively (SO_3^-), while the chromatography of interchangeable anions retains anions so that the functional positively charged groups are utilized (N^+R_4, N^+R_3). That means, to separate anions, stationary phases with positive charges are used, and will be attached to some anion in charge of maintaining the electro-neutrality, which will be displaced by the test analyte for the establishment of the equilibrium.

In Fig. 1.9, the ion exchange chromatographic processes are observed, on the left, cation exchange, and right, anion exchange. The stationary phase shows on the surface ionic functional groups that interact with oppositely charged ions. For anionic chromatography, the process consists of the analytes A^- and B^- of the sample

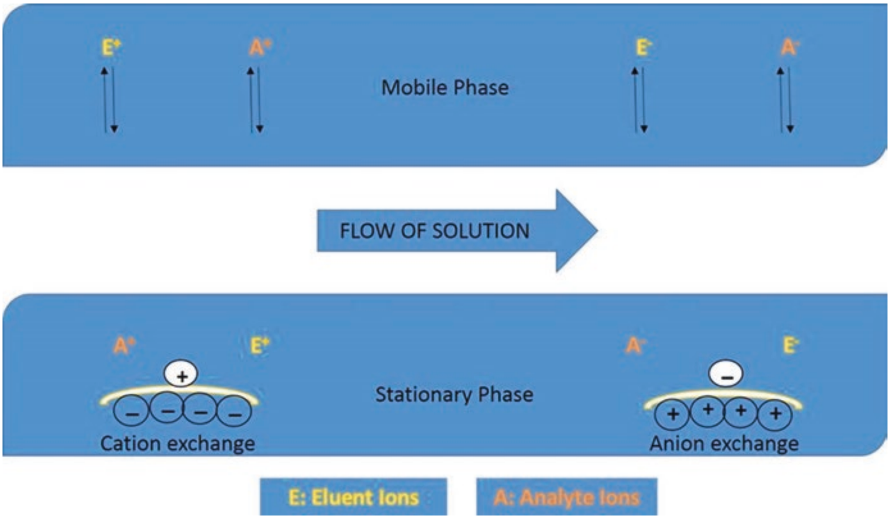


Fig. 1.9 Schematic diagram of the processes in ion chromatography

which are briefly displaced by ions of eluent E^- and retained in resin, before they are interchanged by the eluent ion (Eith et al. 2001).

$$\text{Resina} - N^+R_3E^- + A^- \rightleftarrows \text{Resina} - N^+R_3A^- + E^-$$

5 Materials and Methods

5.1 Description of the Study Area

5.1.1 Localization

The study area is located within the campus of the *Universidad Autonóma de Nuevo León*, UANL, approximately at 8 km in the south of Linares City (Fig. 1.10). This zone is located within the geographical coordinates 24° 47′ of North Latitude and 99° 32′ of West Longitude. This area covers 1000 ha, near to the *Sierra Madre Oriental* (Foroughbakhch 1992).

5.1.2 Topography

The altitude of the study area ranges from 350 to 375 m above sea level; the relief is moderate, figuring hills with slopes of 2–10%; among them are extensive valleys with slight slopes. In some areas, the relief is more pronounced, favoring in this way, intense processes of water erosion (Woerner 1991).

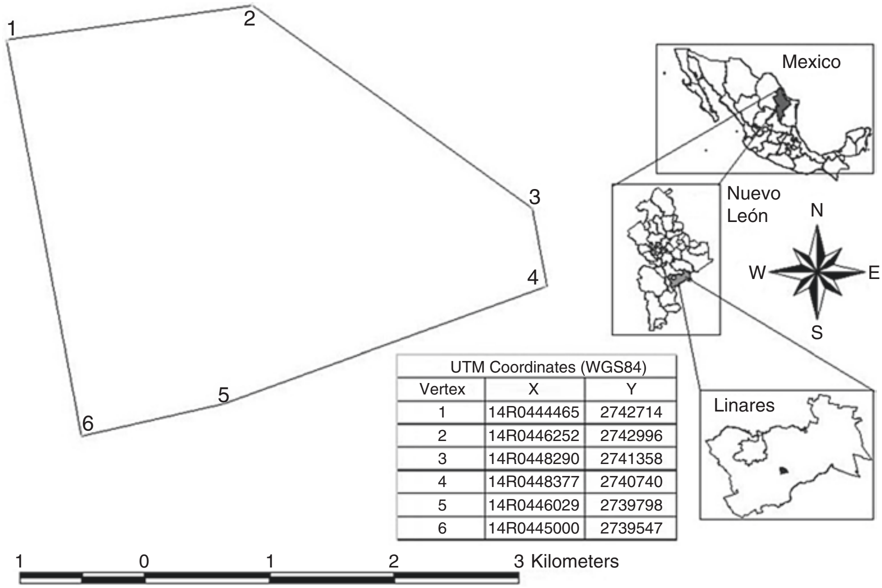


Fig. 1.10 Localization of the study area

5.1.3 Climate

The climate of the region is subhumid temperate, with summer rains of the type (A) C (Wo), according to the classification of Köppen (1931) and with the adaptation to the conditions of the Mexican Republic (García 1987). The annual rainfall is very variable, fluctuating between 400 and 850 mm, concentrating on two periods of summer rain (from March to June and from September to October), and a less rainy and extremely warm period called heat stroke or midsummer drought occurs often in the months of July and August. The average annual temperature is 22 °C, and the maximum temperatures reaching in summer, especially in July and August, are 28–29 °C, with absolute values of 40–45 °C. The coldest period occurs in the months of December, January, and February, with an average temperature of 14–15 °C and extreme minimums of −7 °C (Woerner 1991). Results of maximum, average, and minimum temperatures, as well as precipitation in the year of study, are shown from May 2013 to April 2014 (Fig. 1.11).

5.1.4 Soils

The soils come from the Upper Cretaceous and Pleistocene gravel, with strong cementation, classified as vertisol type of alluvial-colluvial origin, deep and dark color in the flatter part and of type rendzina of origin *lutita calichosa*, and of medium depth in the *lomeríos*. Both types of soil are characterized by high clay content, low

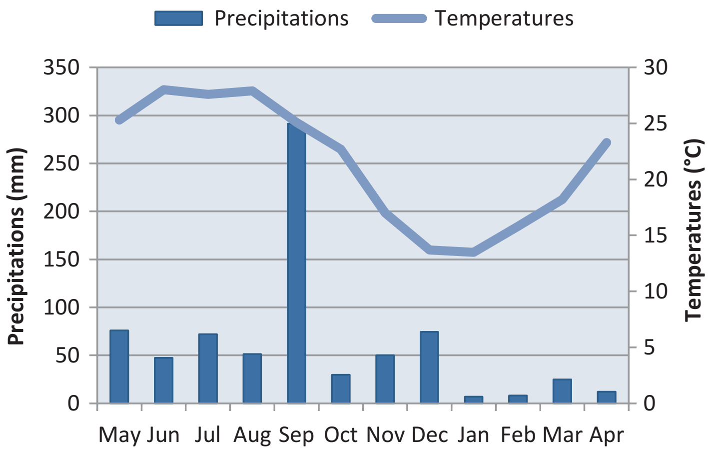


Fig. 1.11 Climogram of the study period

organic matter content, moderately alkaline pH, medium internal drainage, as well as nitrogen and potassium deficiencies (Woerner 1991).

5.1.5 Vegetation

The vegetation in the study area presents a wide floristic variation, as well as high diversity in structure, associations, density, and height. The scrub vegetation in the region of Linares, N.L., is divided as tall thorny scrub with lateral spines with *Acacia rigidula* and *A. berlandieri* as dominant and sub-middle scrub with *Cordia boissieri* and *Havardia pallens* as dominant (Foroughbakhch and Heiseke 1990).

5.2 Description of Treatments, Sampling Methods, and Statistical Analysis

5.2.1 Experimental Design and Selection of Species

A careful run of the study area (Campus of the Faculty of Forestry Sciences of the UANL, Linares, N.L.) was undertaken in order to recognize the species and select the sample individuals where the measurements were carried out. The selection criteria consisted of choosing the woody species characteristic of the scrubland and considering its frequency and abundance (Cabral and Treviño 1989), according to the data registered from the experimental plantations of native species in the campus of forest science faculty, UANL (Foroughbakhch et al. 1987). The species selected for the study are presented in Table 1.5, according to data of Hormazabal (1986), Niembro-Rocas (1990), and Velazco-Macías et al. (2011).

Table 1.5 Characteristics of the five timber species selected for the study

Families	Scientific names	Common names	Characteristics	Distribution
Mimosaceae	*Acacia berlandieri* Benth.	Huajillo	Spiny shrub, fuelwood, natural hardness resistant for rural wood construction, used for handicrafts, firewood, forage	Northeastern and Central Mexico
Mimosaceae	*Acacia wrightii* Benth.	Uña de gato	Spiny tree/shrub, used for forage, firewood, charcoal, food (seeds), handicrafts	Northern Mexico and Southern Texas, USA
Mimosaceae	*Ebenopsis ebano* (Berl.) Barneby	Ébano	Hardwood, dark with very good natural resistance, used as posts, firewood, charcoal, wood (furniture), food	Northern Mexico, Southwestern Texas, in the lowlands
Mimosaceae	*Havardia pallens* (Benth.) Britton and Rose	Tenaza	Spiny shrub, dense wood, low natural resistance, used as firewood and furniture and in construction	North and Northeastern Mexico and Southern Texas
Rutaceae	*Helietta parvifolia* (Gray) Benth.	Barreta	Large shrub or small tree, early invader in calcareous soils, deep root system with very high natural resistance of wood, used as poles, shelves, wood, charcoal, medicine	Northeastern Mexico and Texas

The tests were conducted in two areas: (1) in experimental plantations where the samples were composed of 15 plots of 10 × 10 m, 3 plots per native species, and approximately 25 trees of each species per plot, with a separation of 3 m among them. (2) In the native vegetation area, an inventory was made through transects, along which were randomly delimited, sampling areas of 10 × 10 m (Fig. 1.12) for the arboreal-shrub stratum (three plots per species).

5.2.2 Methods of Sampling

5.2.2.1 Phenological Development of the Timber-Yielding Species of the Tamaulipan Thorn Scrub

Nine trees were selected and tagged (Fig. 1.13a) for monitoring per plot, and the status of each tree was measured every 15 days during 1 year, starting from May 2013 to April 2014, and for that, a visual and quantitative evaluation method in terms of percentage was used (Fig. 1.13b), covering all the periods of the

Fig. 1.12 Delimitation of sampling plots in the native scrubland

Fig. 1.13 Selection and tagging (**a**) of tree samples for phenologic observations (**b**)

manifestation of vegetative and reproductive phases: initiation (Fig. 1.14a), fullness (Fig. 1.14b), and declination (Fig. 1.14c), according to Villasana and Suárez de Giménez (1997).

5.2.2.2 Estimation of Forest Production of Thorn Scrub

The forest potential was evaluated by determining the volume of each species per hectare, taking into account the total height, basal diameter, and diameter at breast height of all the individuals, also including shoots.

These variables were selected to determine the developmental behavior of individuals, since the proportions between height and diameter, between tree crown size and diameter, and between biomass and diameter usually respond to a general rule,

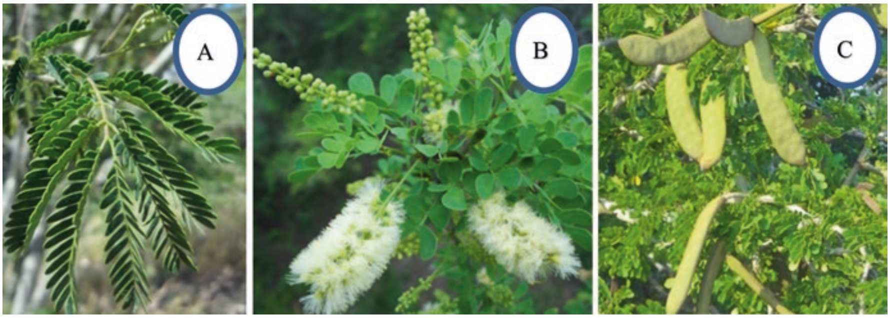


Fig. 1.14 Phenologic phases: (**a**) Foliation (new and immature leaves). (**b**) Flowering (floral buttons and immature flowers). (**c**) Fruiting (mature fruits)

Fig. 1.15 Measurement of (**a**) diameter at breast height, (**b**) basal diameter, and (**c**) total height

which is the same for all trees that develop under the same environmental conditions, being considered from the smallest to the largest (King 1996; Archibald and Bond 2003; Bohlman and O'Brien 2006; Dietze et al. 2008).

5.2.2.2.1 Diameter

The measurement of basal diameter (BD) was undertaken at 0.1 m above the soil surface (Fig. 1.15a), adopting a standard measurement employed for trees and shrubs of the Tamaulipan thorn scrub, according to Gómez (2000), Alanís et al. 2008, and Jiménez et al. (2012). This variable was measured, based on the premise that it supports the generation of relationships for the structuring of allometric equations for estimation of biomass (Méndez 2001), calculating from this, the basal area. Both basal diameter and diameter at breast height (DAP) were measured by a calibrator (Fig. 1.15b).

5.2.2.2.2 Total Height

This dendrometric variable (*h*) forms part of the main interactions for the construction of allometric equations for biomass estimation (Vanclay 2009). It was measured by a beacon, as can be seen in Fig. 1.15c.

5.2.2.2.3 Volume of Wood

The wood volume of each tree was determined according to diameters and total height, applying the formula of Smalian (Moctezuma 2007) with a morphic coefficient factor of 0.6 (Eq. 1.2).

$$V = \left[\left(\left(\frac{D_1}{2} \right)^2 \times \pi + \left(\frac{D_2}{2} \right)^2 \times \pi \right) / 2 \right] \times L \quad (1.2)$$

where V is the volume (m^3/ha) and D_1 and D_2 are diameters (cm) of each section (height).

Once the volume was obtained per tree, the mathematical process was carried out to estimate the volume of wood corresponding to each species.

5.2.2.2.4 Canopy Cover

According to Vanclay (2009), the canopy coverage generally forms part of principal interactions during the construction of allometric equations for the estimation of biomass so that this variable was also considered for the present study. Canfield (1941) and Cantú (1990) define canopy cover as the vertical downward projection of foliage or the upper part of the plant over the soil or also the proportion of soil occupied by the aerial part of the plants.

According to this definition, this variable was determined by recording the perpendicular projections of the aerial part of each tree over the soil, according to the north-south and east-west directions, with the use of metric tape (Fig. 1.16).

From the classical method of calculating the area of a circle, a method adapted to the scrub was developed to calculate the area occupied by each individual (Eq. 1.3).

Fig. 1.16 Measurement of the projection of canopy coverage of tree and shrubs

From this, the total area occupied by each species and the relative area (in percentage) in each plot and then per hectare was determined**.**

$$C = \pi\left(\frac{D_1}{2}\right)\left(\frac{D_2}{2}\right) \tag{1.3}$$

where C is the coverage (m^2) of each tree and D_1 and D_2 are diameters (m) of the canopy projections in the north-south and east-west directions.

Data collected from the plantation and native scrub were ordered together with the results of a study realized by Foroughbakhch et al. (1987) in the same plantation selected in the present study; this study presents results of basal diameter and total height from 1984 to 1987, comparing different mathematical models that obey the general form of Height = f (diameter).

5.2.2.3 Direct Quantification of Potential Productivity of Experimental Plantations of the Tamaulipan Thorn Scrub

The direct quantitative method is applied in the area planted, and this consisted of deriving data from each tree in each plot for obtaining the exact production of each species with the values estimated (Fig. 1.17).

5.2.2.4 Quantification of Forage Biomass of the Tamaulipan Thorn Scrub

The determination of potential forage was realized through quantification of foliar biomass of the strata tree-shrub as well as the litterfall of each strata and the development of herbaceous associated with each species.

Fig. 1.17 Measurement of fresh weight of the components of the derived trees

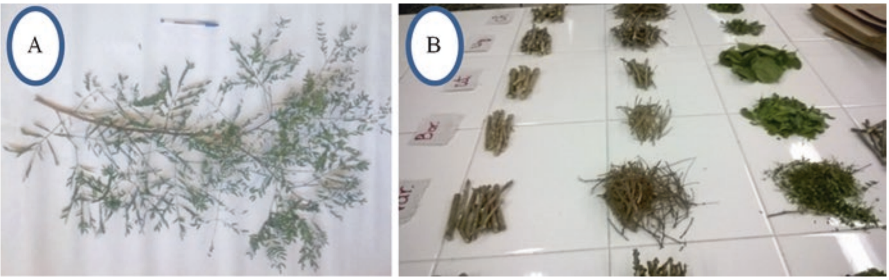


Fig. 1.18 Sampling for leaf biomass through the "Adelaide" method: (**a**) reference branch, (**b**) separation of the branch in different components (leaves, stem 1, stem 2)

5.2.2.4.1 Foliar Biomass of Tree-Shrub Strata

The visits undertaken to determine foliar biomass were realized during the four seasons of a year (from summer 2013 to autumn 2014), and the "Adelaide" or hand reference method was used (Foroughbakhch et al. 1996), which consisted of selecting a branch denominated "unit of reference," representative of the species of interest in form and foliar density. Later, the number of hand units that each tree contained in the four cardinal points of the crown was counted, and the unit reference sample of each species was taken to the laboratory to separate it into leaves, twigs <1 cm (stem 1), and twigs >1 cm (stem 2) as shown in Fig. 1.18; and the plant material was dried in an oven at 65 °C until constant weight was obtained to estimate the dry leaf biomass of these species.

5.2.2.4.2 Litterfall Production of Shrub-Arboreal Stratum

For the quantification of litterfall, the methodology used was the one proposed by Návar and Jurado (2009), which consisted of collecting the fallen leaves through wooden trap of 1 m^2, with hole of 1 mm^2 placed at the base of the trees. The traps were randomly distributed in the plots and maintained in their original positions during the whole period of time of sampling (1 year), and the materials were collected periodically every 15 days from May 2013 to April 2014, removing the rests or materials of other species (Fig. 1.19). The collected litterfall was taken to the laboratory and dried in an oven at 65 °C for 72 h.

5.2.2.4.3 Biomass of Herbaceous Vegetation

In each plot, an inventory of the herbaceous plants was carried out through transects along which three sampling areas of 1 × 1 m (subplots) were randomly distributed and by a wooden frame, recording in them: species, number, height, crown surface, basal area, and diameters. These data were recorded to characterize the herbaceous species according to the method of point interception of Mueller-Dumbois and Ellenberg (1974), which consisted of noting the species that is located under the points of interception of the wires of the grid formed by the wooden box, divided every 10 cm (Fig. 1.20a).

Fig. 1.19 Collection of litterfall through wooden trap

Fig. 1.20 Record of data of the herbaceous stratum: (**a**) characterization of herbaceous by method of points of interception, (**b**) total plot cut, (**c**) collection of herbaceous plant material, (**d**) drying, (**e**) place in desiccator to keep the sample dehydrated, (**f**) weight of herbaceous biomass

The biomass produced in each sampling subplot of 1 m^2 was determined by the direct method of total plot cutoff, which consisted of harvesting within the subplot of 1 × 1 m; all plant materials are cut at the ground level (Fig. 1.20b, c). The harvested green biomass was dried in an oven at 65 ± 5 °C for 48 to 72 h until constant weight (Fig. 1.20d). The final weight was recorded as anhydrous biomass (Fig. 1.20e).

The floristic diversity of the herbaceous was determined by the evaluation of the ecological attributes proposed by Mueller-Dumbois and Ellenberg (1974), when applying the four equations of affinity of Sørensen (1948) (Eqs. 1.4–1.7):

$$\mathrm{FR} = \frac{\mathrm{Fi}}{F} \times 100 \tag{1.4}$$

Fig. 1.21 Felling of tree samples for chemical and energy analysis

where FR is the relative frequency, Fi the frequency of a species, and F the frequency of all the species.

$$\mathrm{DR} = \frac{\mathrm{Ni}}{N} \times 100 \tag{1.5}$$

where DR is the relative density, Ni the number of individuals of a species, and N the number of individuals of all the species.

$$\mathrm{CR} = \frac{\mathrm{Ci}}{C} \times 100 \tag{1.6}$$

where CR is the relative coverage, Ci the coverage of a species, and C the coverage of all the species.

$$\mathrm{VI} = \frac{\mathrm{FR} + \mathrm{DR} + \mathrm{CR}}{3} \tag{1.7}$$

where VI is the importance value.

5.2.2.5 Energy Characterization and Chemical Composition

5.2.2.5.1 Preparation of Samples

In each plot of experimental plantations, one representative tree of the community was derived, without any visible defects (Fig. 1.21).

The trees collected from each subplot were divided to obtain material of different components (trunk, branches, twigs, and leaves). Parts of the trunks and branches were cut into test pieces of 2 cm in length, which were placed in a humidity conditioning chamber (65% relative humidity) and controlled temperature (20 °C) to homogenize them to a content of moisture (CH) of 12% (Fig. 1.22a), so that all the specimens had the same moisture content before being submitted to the carbonization process (Fig. 1.22a). The other parts of trunks and branches, together with

Fig. 1.22 Preparation of samples: (**a**) conditioning of test pieces in the chamber, (**b**) drying of chips in air

the twigs and leaves, were chipped and air-dried until reaching approximately C.H. of 10% (Fig. 1.22b), according to the procedure of Chife (2005), taking into account that the drying of the plant material should be carried out at moderate temperature conditions to prevent the volatile compounds from dissipating in the atmosphere.

5.2.2.5.2 Process of Carbonization

After 30 days of conditioning in the chamber, the test pieces were carbonized by metallic cylinders that were closed with lids, in order to avoid the entry of oxygen during combustion in electric oven, at temperature of 650 °C for a period of 3 h (Fig. 1.23a) according to Briseño et al. (2015). Previously there were five samples per species and per component of the tree (trunk and branches). At the end of the carbonization cycle, there was a cooling period and then proceeded to discharge (Fig. 1.23b).

5.2.2.5.3 Determination of Yield in Charcoal

The carbon obtained was conditioned to the environment. The weight and the measurements in the longitudinal, radial, and tangential planes, as initially performed on the wood samples, were recorded, and then the yield was calculated by Eq. 1.8:

$$\text{Yield} = \left(\frac{Wc}{Wd}\right) \times 100 \tag{1.8}$$

where Wc is the weight of charcoal and Wd, the dry weight of wood.

The sampled coal was milled in an ultracentrifugal mill (mark RETSCH, model ZM 200) and automatically screened in the same equipment (Fig. 1.24a), at a particle size of 425 μm for posterior immediate analysis. The chips and dried leaves were milled in a Wiley equipment, Model 4 Bench, 115 V, 50/60 Hz (Fig. 1.24b); the obtained flour was classified with sieves (Fig. 1.24c), and the fraction contained between 40 (425 mm) and 60 (250 mm) meshes was used according to the T 257 cm-85 standard (TAPPI 2000) for chemical analysis.

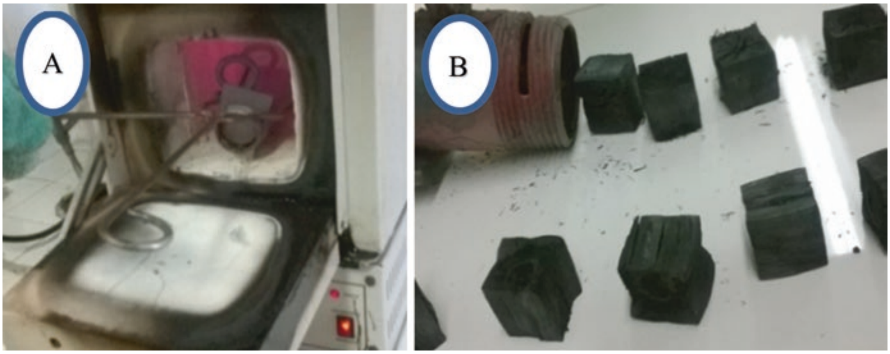


Fig. 1.23 Carbonization of test pieces: (**a**) in furnace, (**b**) final product in cooling and discharge

Fig. 1.24 Preparation of samples through (**a**) milling of charcoal, (**b**) milling of chips and dry leaves, (**c**) sieves of 40 and 60 holes

The milling was done after drying the plant material as recommended by Pérez (2009), to avoid the risk of contamination by fungus. In addition, according to Rivero Martínez et al. (2002) who evaluated the influence of the preparation of the vegetal raw material on the yield of the extraction process, the grinding of the material must be done after drying in order to obtain a smaller and homogeneous particle size, which favors the union of the cells with the solvent as there is a greater contact surface between the latter and the plant material. In fact, the success of lixiviation depends to a great extent on the form and dimension of the solids, since to a smaller particle size, there are greater surface area of contact among the drug and the solvent and therefore greater access to the active substances to the liquid medium. However, very small particle sizes lead to the formation of too fine powders, which can cause problems in the extraction process. Samples of size 425 μm (Fig. 1.25) were used for both the immediate and elemental analyses.

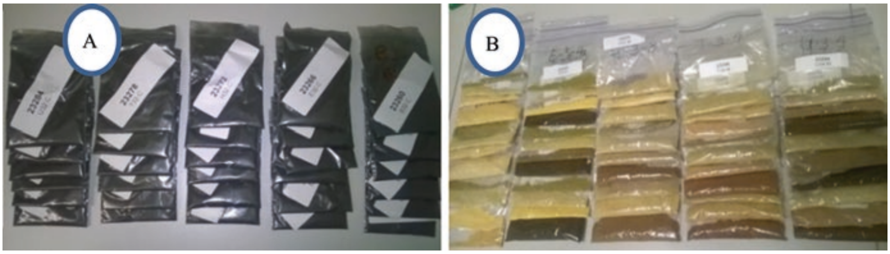


Fig. 1.25 Samples of size 425 μm: (**a**) charcoal of trunk and branches, (**b**) flour of trunks, branches, twigs, and leaves of the five studied species

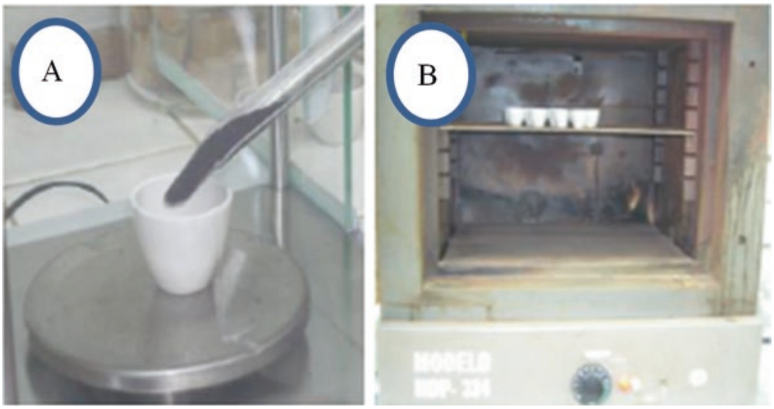


Fig. 1.26 Determination of moisture content: (**a**) sampling, (**b**) drying in oven

5.2.2.5.4 Proximate Analysis

The physical-chemical properties of each sample were analyzed according to the international standard ASTM D 1762-84 (ASTM 2001), in the Wood Technology Laboratory, Faculty of Forestry Sciences UANL, Linares, Nuevo Léon, Mexico.

The immediate analysis method evaluates the quality of the solid biomass in terms of percentage of the moisture content (MC), volatile material (VM), ash (A), and fixed carbon (FC), according to FAO (1983) and Kretschmann et al. (2007).

5.2.2.5.4.1 Moisture Content

Crucibles were placed in a muffle (Arsa type, model AR 340) at 750 °C for 10 min, and after cooling in the desiccator, the initial weight (Wi) of the crucible was recorded. One gram (1 g) of each sample was weighed in the crucibles, with an analytical balance OHAUS Model 300 g × 0.001 g (Fig. 1.26a). Samples were then placed in a drying oven (Model HDP-334) at 105 °C for 3 h (Fig. 1.26b) and allowed to cool to obtain dry weight (Wd).

The registered data permitted to calculate moisture content (MC), applying the Eq. 1.9:

$$MC = \left(\frac{Wi - Wd}{Wi}\right) \times 100 \tag{1.9}$$

where MC is the moisture content, Wi the initial weight registered before drying, and Wd the dry weight.

5.2.2.5.4.2 Volatile Material

The determination of the volatile compounds was done by gradually placing the crucibles with respective lids in the muffle (characteristics) at a temperature of 950 °C, according to a process which started with the crucibles in the muffle door for 2 min (Fig. 1.27a), then at the entrance for 3 min (Fig. 1.27b), and finally at the bottom (Fig. 1.27c), with the door closed for 6 min, in order to avoid a rapid waste.

The percentage of volatile was calculated by applying the formula of Eq. 1.10:

$$VM = \left(\frac{Wd - Wv}{Wd}\right) \times 100 \tag{1.10}$$

where VM is the content of volatile material, Wd is the weight of charcoal after submission at 105 °C, and Wv is the weight of charcoal after submission at 950 °C.

5.2.2.5.4.3 Ash Content

The crucibles without lids were placed in the muffle at 750 °C for 6 h, plus an additional hour, to achieve total incineration of the charcoal, which was checked by observing a whitish color of the ashes. They were left to cool to obtain their weight,

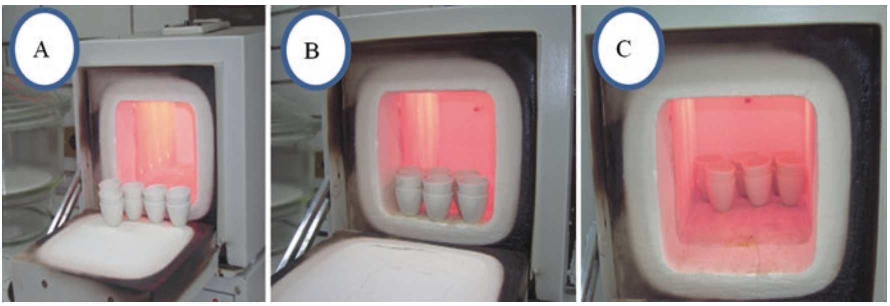


Fig. 1.27 Process of determination of the volatiles with different positions of crisols in furnace: (**a**) in the door, (**b**) in entry, (**c**) at the bottom

discounting the weight of the crucibles. The ash content (*C*) was determined by Eq. 1.11:

$$A = \left(\frac{\text{Wa}}{\text{Wv}}\right) \times 100 \tag{1.11}$$

where *A* is the ash content, Wa is the weight of ash, and Wv is the weight after submitting the sample at 950 °C.

5.2.2.5.4.4 Fixed Carbon

For calculating the percentage of fixed carbon, the moisture content, volatile material, and ash were subtracted from the mass of the milled and sieved coal using Eq. 1.12, according to Márquez-Montesino et al. (2001).

$$\text{Cf} = 100 - \left(\text{MC} + \text{VM} + A\right) \tag{1.12}$$

where Cf is the fixed carbon, MC the moisture content, VM the content of volatile material, and *A* the ash content.

5.2.2.5.4.5 Calorific Value

The calorific value (CV) was calculated from the fixed carbon content (Cf) and volatile material (VM), according to following formula of Eq. 1.13, described by Cordero et al. (2001).

$$\text{CV} = 354.3\ \text{Cf} + 170.8\ \text{VM} \tag{1.13}$$

5.2.2.5.5 Elemental Analysis

The elemental analysis is a technique which estimates total content of carbon, hydrogen, nitrogen, and sulfur present in a wide range of natural organic and inorganic samples, such as solids and liquids (Vassilev et al. 2013). The analysis was done according to the International Standard EN 15103, in the laboratory of fuel, soil, and environmental analysis in the University of Applied Sciences and Arts (HAWK), Faculty of Resource Management, Göttingen, Germany. The technique consisted of placing approximately 5–10 mg of dry and ground sample into a piece of tin weighted at 0.01 mg and rolled in a hermetic ball (Fig. 1.28a, b). During the analysis, the samples were taken to combustion in a pure oxygen environment in an equipment CHN Analyzer, Vario EL III type, from Elementar GmbH (Fig. 1.28c), at a temperature of 1050 °C.

With that combustion process, the organic molecules of the samples are converted to simple gases (CO_2, H_2O, and N_2). The generated gases are driven with helium (He) through reagents that reduce the number of gaseous species present in

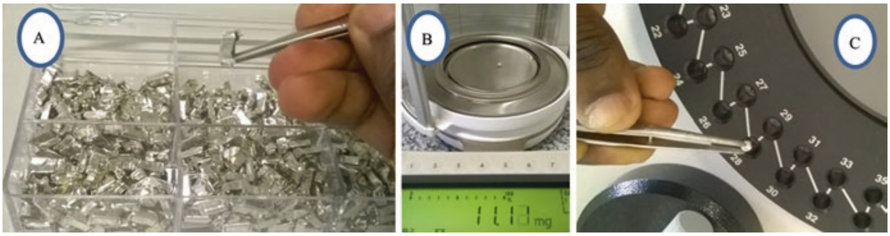


Fig. 1.28 Preparation of samples for elemental analysis: (**a**) tin pot, (**b**) samples rolled in tin pot and in hermetic balls and weighed, (**c**) placing the balls in the equipment *CHN Analyzer*

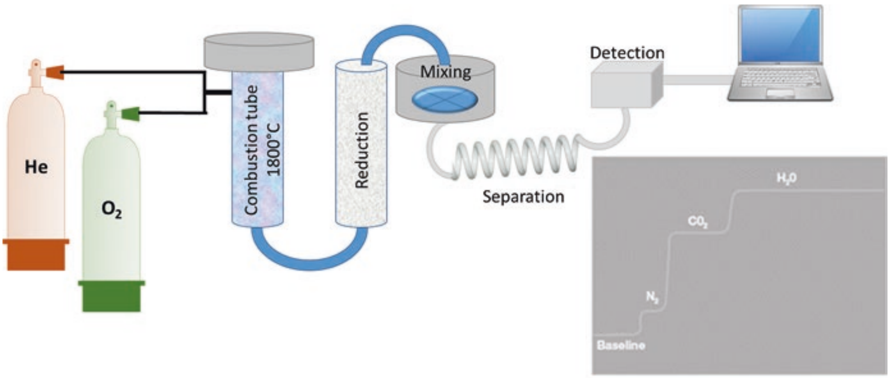


Fig. 1.29 Process of determination of the organic elements *CHN* by combustion and reduction of gases obtained

the mixture resulting from the combustion (Fig. 1.29). The gases produced are then pressurized and separated by means of a chromatographic column, which allows measuring the quantity of each of them owing to their different thermal conductivities from which the content of N, C, and H of each sample was evaluated. The oxygen is absorbed in a tube that is reduced to copper. Nitrogen arrives directly at the thermal conductivity detector; water and CO_2 are absorbed into two different absorption tubes and subsequently released by heating of the columns. The calibration of the instrument was performed with acetanilide, which is also used to calculate the daily correction factors for calibration.

This technique is essential for the synthesis chemist since it provides data that contribute to the confirmation of the structure of a newly prepared compound and help to establish the identity and purity of any type of sample with the mentioned elements.

5.2.2.5.6 Compositional Analysis

The chemical components were analyzed from the original samples (wood flour, twigs, and leaves). The contents of holocellulose, lignin, extractables, and inorganic substances were determined (Ávila-Calderón and Rutiaga-Quiñones 2014).

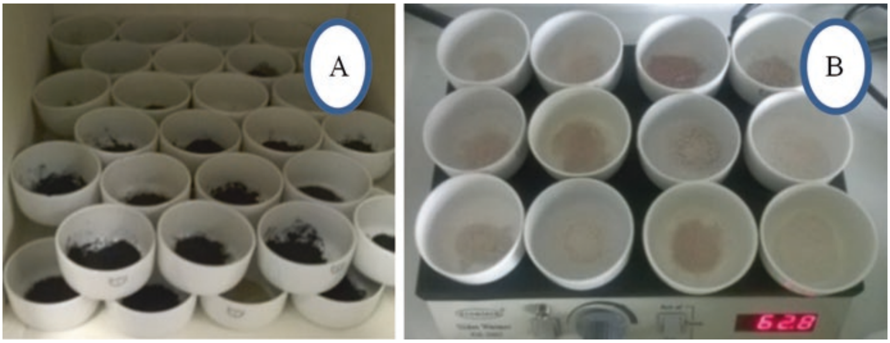


Fig. 1.30 Determination of ash content: (**a**) samples in muffle for combustion, (**b**) cooling of ashes, products of combustion

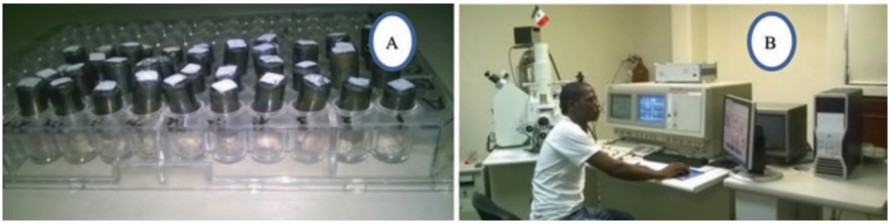


Fig. 1.31 Microanalysis of ashes: (**a**) mounting of samples, (**b**) microscopic observation

5.2.2.5.6.1 Inorganic Substances

The percentage of ash was determined according to the standard ISO 17225-1 (2014), in the laboratory of fuel, soil, and environment analysis of the University of Applied Sciences and Arts (HAWK), Faculty of Resource Management, Göttingen, Germany. Each sample ranging between 35 and 45 g was passed in crucibles and placed in furnace Nabertherm l5/12 of 5 L, model of 1200 °C ref. L050K2CN in programmation P330 (Fig. 1.30a). After a time of cooling in a desiccator (Fig. 1.30b), the weight of the ash obtained was registered and its percentage was calculated.

5.2.2.5.6.2 Microanalysis of Ashes

The microanalysis of the ashes was carried out at the Metallurgy Laboratory of the Metallurgical Research Institute of the *Universidad Michoacana de San Nicolás de Hidalgo*, Morelia, Mexico.

The different elements that constitute the ashes were identified and quantified by means of their partial microanalysis in an X-ray spectrometer, coupled with an Electronic Scanning Microscope Jeol model JSM-6400. The ash samples were previously mounted on a carbon support (Fig. 1.31a), for microscopic analysis (Fig. 1.31b).

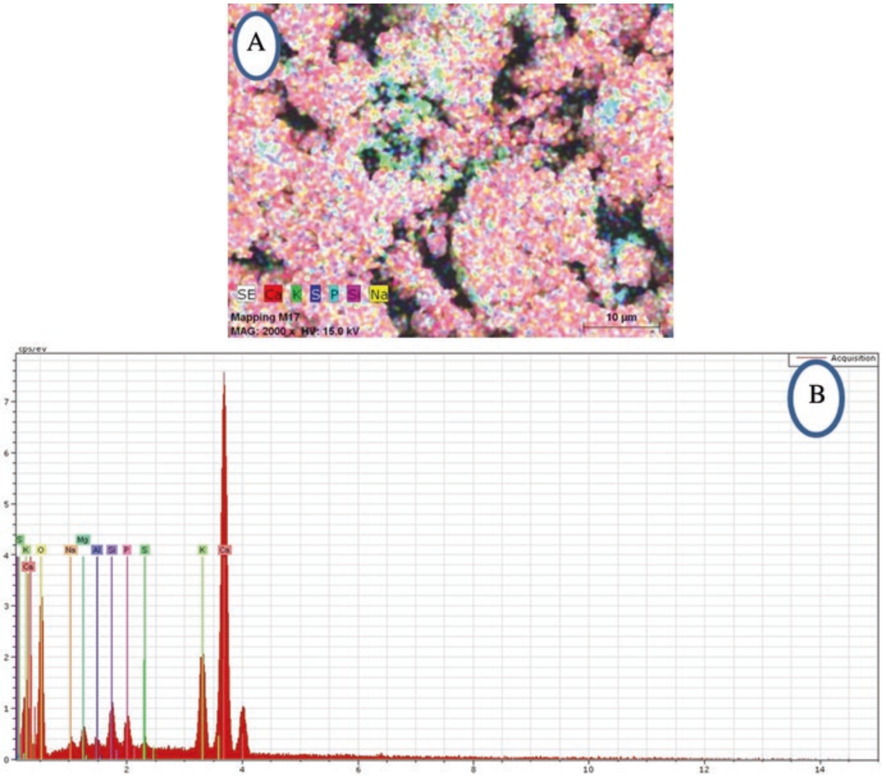


Fig. 1.32 Microanalysis of ashes: (**a**) granulometric distribution of ashes elements, (**b**) spectra of X-ray energy dispersion for ash elements at random points

The conditions of operation were 20 kV and 8.5 s (Téllez et al. 2010), obtaining the granulometric distribution of each sample (Fig. 1.32a) and the respective spectra at random points (Fig. 1.32b).

5.2.2.5.6.3 Extractable Substances

The extractions were carried out in the laboratory of management and utilization of vegetal resources of the Botany Department, Faculty of Biological Sciences, UANL.

Based on the Schwanninger and Hinterstoisser (2002) methodology, the extractables were determined by applying a solid-liquid successive extraction to wood flour (from 8 to 13 g) in soxhlet equipment (Fig. 1.33a), with 200 mL of solvents with increasing polarity: cyclohexane, acetone, methanol, and distilled water under reflux. The extraction period with each solvent was 6 h, after which the extractables were separated from the solvents by a Yamato BM 100 rotary evaporator (Fig. 1.33b), at 45 °C temperature, applying vacuum under reduced pressure.

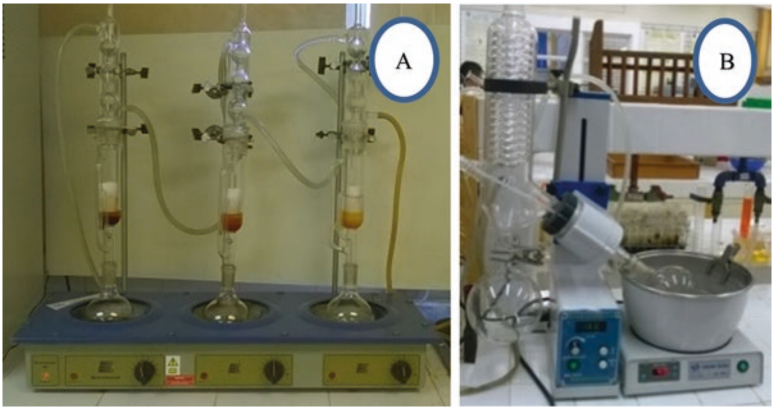


Fig. 1.33 Determination of extractables. (**a**) Successive extraction in soxhlet equipment, (**b**) separation of extractables in rotary evaporator

The extractable content for each solvent was calculated by dividing the weight of the anhydrous extract by the weight of the anhydrous flour, in percentage (Eq. 1.14):

$$\text{Extractables} = \left(\frac{\text{Wa} - \text{Wrs}}{\text{Wm}} \right) \times 100 \tag{1.14}$$

where Wa = anhydrous weight of extractables, Wrs = anhydrous weight of solvent residue, and Wm = anhydrous weight of the milled wood sample.

The total extractables were calculated with the sum of the percentage of extractables of each solvent. The wood flour, after successive extraction, was designated as flour free of extractables and was used to determine the lignin content.

5.2.2.5.6.4 Lignin

The lignin content in wood flour free of extractables was determined according to the Runkel and Wilke (1951) technique, in the Laboratory of Chemistry and Chemical Wood Technology, Faculty of Engineering in Wood Technology, *Universidad Michoacana de San Nicolás de Hidalgo*, Morelia, Michoacan, Mexico. To 1 g of wood flour free of extractables, 50 mL of sulfuric acid 72% and 50 mL of hydrobromic acid 40% were added, shaking it and leaving to rest for 2 h (Fig. 1.34a, b). Later, 200 mL of distilled water was added and boiled for 5 min. Then, it was filtered into Büchner funnels, using filter paper Whatman No. 40, and the samples were repeatedly washed until acid residues were removed (Fig. 1.34c). Finally, they were brought to constant weight in a furnace at 103 °C (Fig. 1.34d) before passing in a desiccator (Fig. 1.34e) to avoid moisture consumption.

Fig. 1.34 Determination of lignin content: (**a**) preparation of solutions H_2SO_4 and HBr, (**b**) addition of acids to the flour sample, (**c**) extractable filtering and washing of acid residues, (**d**) drying in furnace, (**e**) desiccator with lignin samples, (**f**) lignin

The content of lignin was calculated by dividing the weight of anhydrous sample by the weight of anhydrous flour free of extractables, in percentage (Eq. 1.15):

$$\text{Lignin}(\%) = \left(\frac{\text{Wl}}{\text{Wa}}\right) \times 100 \tag{1.15}$$

where Wl is the weight of lignin and Wa the weight of the anhydrous sample.

5.2.2.5.6.5 Holocellulose

The content of holocellulose (cellulose and hemicellulose) was calculated by difference, subtracting the lignin, extractable, and ash percentages of 100%, from the summative analysis developed by Mocchiutti (2007), according to Eq. 1.16:

$$\%\text{Extractables} + \%\text{Lignin} + \%\text{Holocelulose} + \%\text{Ash} = 100\% \tag{1.16}$$

Fig. 1.35 Determination of pH: (**a**) samples in beakers, (**b**) reading in potentiometer

5.2.2.5.7 Physical Properties

The physical properties that were determined in the wood were pH and experimental calorific value.

5.2.2.5.7.1 pH

The determination of the pH was done according to the methodology described by Sandermann and Rothkamm (1959), in the laboratory of chemistry and chemical technology of wood, Faculty of Engineering in Wood Technology, *Universidad Michoacana de San Nicolás de* Hidalgo, Morelia, Michoacan, Mexico. The process consisted of placing 2 g of wood flour without extracting into a beaker (Fig. 1.35a), with 20 mL of distilled water, and recording the initial pH and then the pH at 5 min, at 4 h, at 24 h, and finally at 48 h. For this purpose, a potentiometer HANNA was used (Fig. 1.35b).

5.2.2.5.7.2 Experimental Calorific Value

The calorific value was determined experimentally according to the standard ISO 17225-1 (2014), in the laboratory of fuel, soil, and environmental analysis of the University of Applied Sciences and Arts (HAWK), Faculty of Resource Management, Göttingen, Germany. The process consisted of making a pellet from about 1 g of flour of each sample, using a laboratory press (Fig. 1.36a). The pellet was placed in a fuel crucible (Fig. 1.36b, c), with 5 μL of paraffin at 46,260 J g^{-1} to ignite the ignition wire firmly attached to the electrodes of the lid of the calorimetric pump (Fig. 1.36d), so that it touches the fuel, to provoke ignition. The pump is a stainless steel container, with a hermetic closure which allows reaching inside, through two electrodes, an electric current that passes through a fusible wire in contact with the pellet. Before closing the pump, 5 mL of water was introduced to absorb the heat that will release the fuel. Later, about 20–30 atmospheres of oxygen were added, necessary for combustion. The pump was placed inside a calorimeter IKA, C 7000 (Fig. 1.36e), insulated from the outside and of adjustable temperature, to avoid heat loss to the outside.

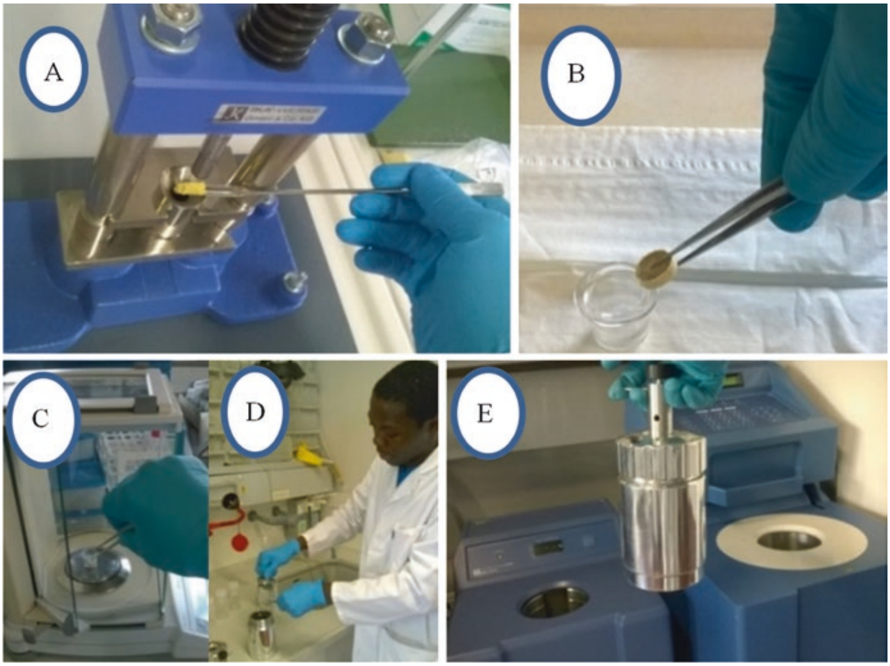


Fig. 1.36 Determination of calorific value in a calorimetric pump: (**a**) manufacture of pellets by hand press, (**b**) pellet in the crucible for combustible, (**c**) weight of the sample pellet, (**d**) calorimetric pump and cover for combustion, (**e**) calorimeter

When the current is supplied to the wire, it melts and burns the fuel pellet, yielding its heat of combustion, through the walls of the pump to the water, so that by measuring the temperature increase experienced by it, and being previously calibrated the system, the calorific value of the fuel can be determined, as indicated by Eq. 1.17 (ISO/CD 18125 o EN 14918):

$$qv, gr, d = qv, gr \frac{100}{100 - Mad} \quad (1.17)$$

where qv, gr, d is the high calorific value at a constant volume of dry fuel in joules per gram; Mad, the moisture of the sample, in percentage of mass; and qv, gr the high calorific value at a constant volume of the fuel as analyzed, in joules per gram.

5.2.2.6 Characterization of Biofuels with the Environment

The effect of solid biomass combustion on the environment was determined through the analysis of sulfates and chlorides in the laboratory of fuel, soil, and environmental analysis of the University of Applied Sciences and Arts (HAWK), Faculty of Resource Management, Göttingen, Germany.

Fig. 1.37 Analysis of post-combustion residue: (**a**) recovery and dilution of the residues, (**b**) cooling of diluted solutions, (**c**) ionic chromatography and data record

With 100 mL of distilled water, the residues resulting from the combustion performed to determine the calorific value were recovered (Fig. 1.37a), and the collected samples were preserved in refrigeration at 4 °C in plastic bottles (Fig. 1.37b), for a period of no more than 28 days, since certain bacteria can reduce sulfate to sulfide, as is the case especially in contaminated waters.

Sulfate and chloride were analyzed by ionic chromatography, which is one of the most efficient methods for the analysis of traces of anions and cations, an absolutely essential technique in the analysis of water and the environment. Based on the procedures proposed by Manahan (2007), the method consists of passing the fluid over a solid cationic and/or anionic exchanger, replacing the cations and/or anions with the hydrogen ion (H^+) and/or the hydroxyl ion (OH^-), respectively (Fig. 1.37c).

The SO_4^{2-} and Cl^- content of each sample was obtained from the calibration curve previously obtained. Calibration was performed with three control solutions (3, 5, and 7) at different concentrations (1, 5, and 10 mg/L, respectively). The chromatogram of Fig. 1.38 shows the result of the selectivity of the solution prepared with the anions, the reason for the investigation, as well as the retention times of each of them.

The concentrations of SO_4^{2-} and Cl^- varied as may be observed in Table 1.6.

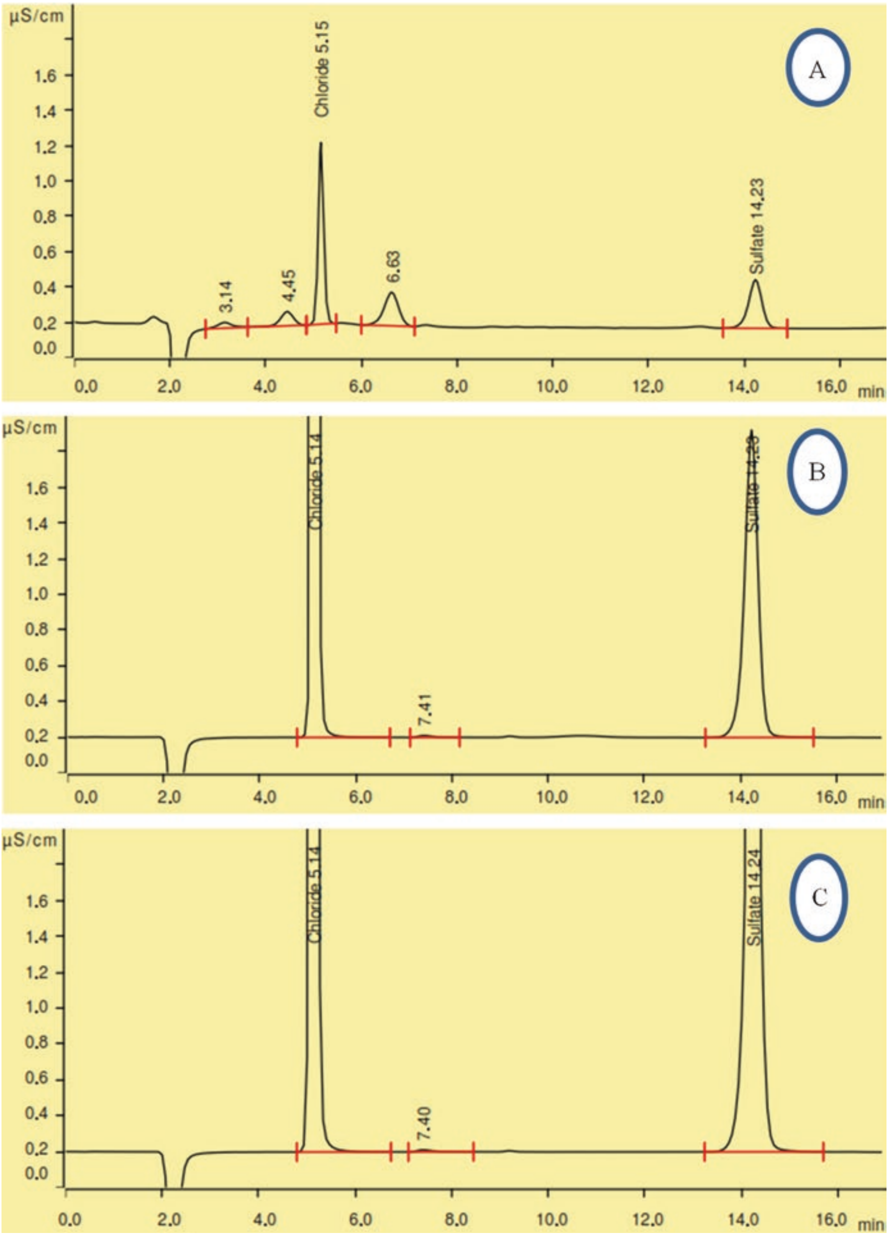


Fig. 1.38 Chromatogram of Cl^- and SO_4^{2-} anions in standard solutions: (**a**) standard 3 at 1 mg/L, (**b**) standard 5 at 5 mg/L, and (**c**) standard 7 at 10 mg/L

Table 1.6 Concentrations of SO_4^{2-} and Cl^- in the standard solutions

Peak number	Retention time (min)	Area (μS/cm) × min	Height (μS/cm)	Concentration (mg/L)	Component name
1	3142	0.0120	0.032	Invalid	
2	4448	0.0260	0.080	Invalid	
3	5148	0.1378	1.028	0.868	Chlorides
4	6628	0.0676	0.190	Invalid	
5	14,232	0.0906	0.275	0.836	Sulfates

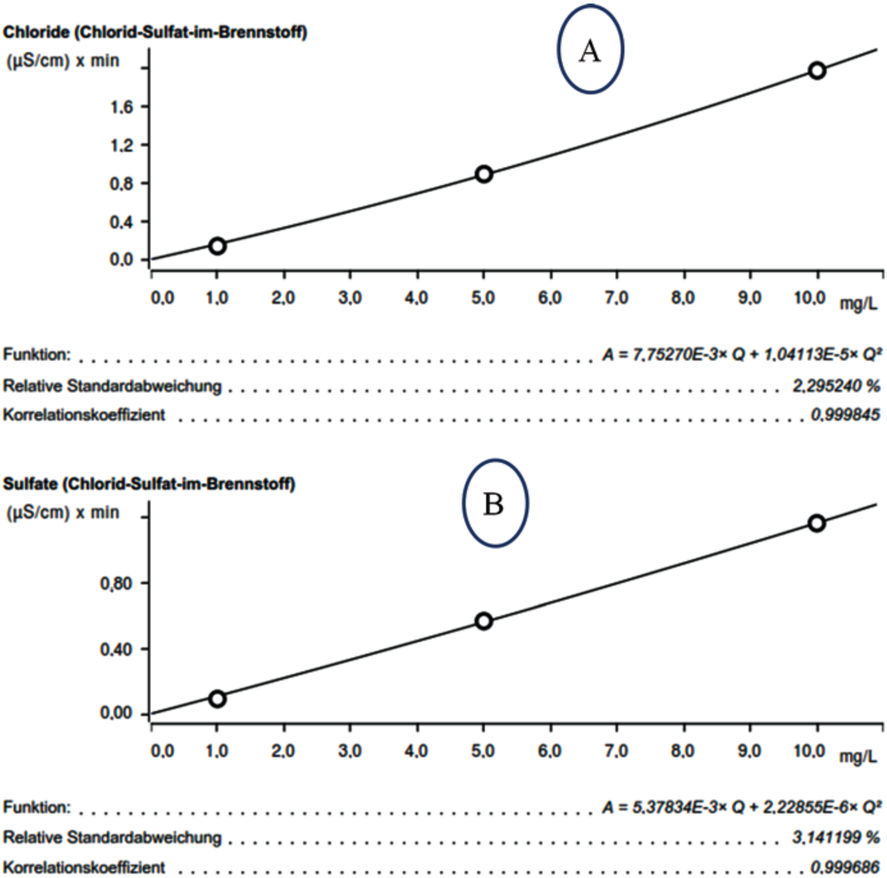


Fig. 1.39 Calibration curves of anions in standard solutions at different concentrations through the Magic Net program: (**a**) SO_4^{2-} and (**b**) Cl^-

In this way, a chromatogram was obtained for each sample and the concentrations generated of SO_4^{2-} and Cl^- were registered for statistical analysis.

Although different concentrations of SO_4^{2-} and Cl^- were registered for the standard samples, the calibration curve showed similar results (Fig. 1.39a, b), which validates the trend of the results. In this graph, we observe the calibration curve for SO_4^{2-} and Cl^-, the curve equation, the standard deviation obtained, and the correlation coefficient. In addition, the graph shows the concentration of anions (ppm) versus area (μS cm^{-1} min), and a good correlation is observed according to its coefficient *r* of 0.9998 and 0.9996 for SO_4^{2-} and Cl^-, respectively.

5.2.3 Statistical Analysis

The statistical package used for the analysis of scrub productivity data was SPSS version 21; the statistics practiced included an analysis of variance to verify significant differences between growth variables (diameters, height, and volume) and biomass (leaf biomass, litterfall, herbaceous), with a 95% confidence interval. The Tukey's test was used to determine groups of homogeneity between species and between sites for the aforementioned variables, at a confidence level of 95% ($P = 0.05$) according to Zar (2010).

For coverage, the experimental design used for the present study was "Design of Random Blocks with Factorial Arrangement." This, in order to consider the original arrangement of the plantation (Gutiérrez and De la Vara 2012). For that purpose, two factors were determined, as described below: Factor A corresponds to the effect of the type of site, corresponding to two levels, native area and experimental planting. Factor B refers to the effect produced by the plant species being five levels, *Helietta parvifolia*, *Ebenopsis ebano*, *Acacia berlandieri*, *Havardia pallens*, and *Acacia wrightii*.

Since the data resulting from the immediate analysis are percentage values, they were transformed with the sum of square function of the *P* arcsine, where *P* = a proportion of the dependent variable (Schefler 1981). Later, the normality tests were performed for each variable, through the Kolmogorov-Smirnov test. The significance of the obtained results was determined by an experimental design with a criterion of randomly complete blocks. In the cases where significant differences were observed, the Tukey's multiple comparison tests (Steel and Torrie 1980) were performed at 95% confidence level ($P = 0.05$).

The values of the chemical components (extractables, lignin, holocellulose) and physical variables (pH, calorific value) were processed through an analysis of variance with one factor and four levels (trunk, branches, twigs, and leaves) using Statgraphics program, version 7.0. The probability value (α) established to qualify as significant to the differences found in the source of variation was 0.01.

6 Results

6.1 Phenological Development of the Species Studied

The results of phenological study of each species are presented according to the vegetative (foliation) and reproductive (flowering and fruiting) phenophases.

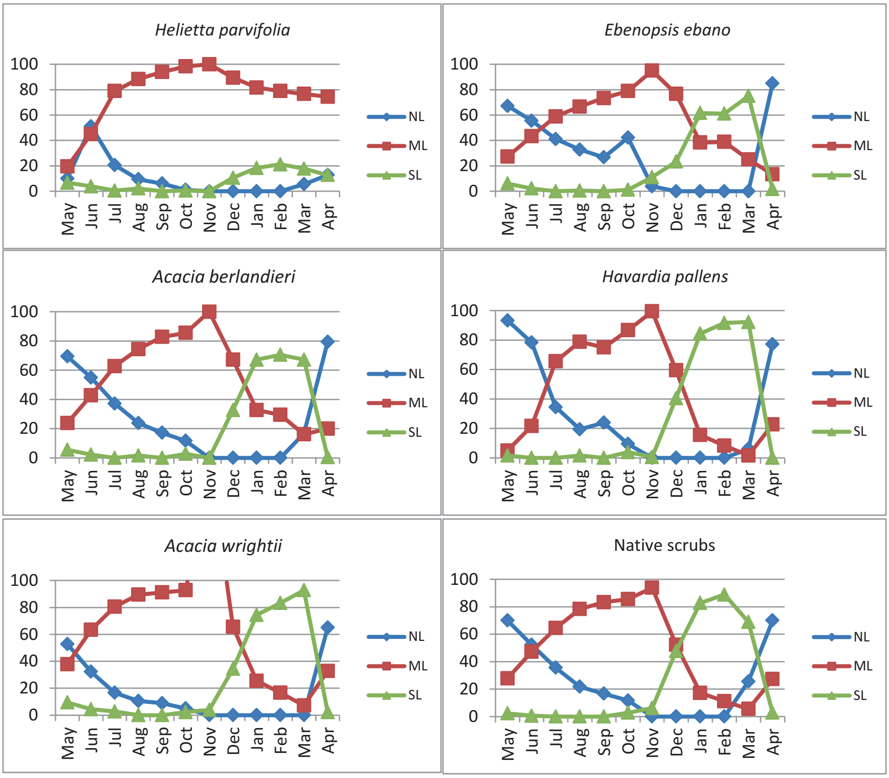


Fig. 1.40 Vegetative development of five species of the Tamaulipan thorn scrub from May 2013 to April 2014. *NL* new leaves, *ML* mature leaves, *SL* senile leaves

6.1.1 Foliation

The vegetative development presented significant differences ($P < 0.05$) both among species and by plant formation type, with a similar pattern in all species, both in experimental plantations and native scrub (Fig. 1.40), with a temporal and quantitative irregularity of the different phenophases. The formation of new leaves was found mainly during spring and autumn (May to October) in the year of study, with peaks in spring (April and May). The percentage of renovation of leaves oscillated between 50 and 100%, being *Havardia pallens* the species with higher renovation (95–100%) and *Helietta parvifolia* the species with lower renovation (50%). As they are concerned, *Ebenopsis ebano*, *Acacia berlandieri*, and *Acacia wrightii* renewed their leaves at 70–85%, 70–80%, and 55–70%, respectively. This vegetative development coincided with the rains of late summer and early autumn, although the percentage of leaf shoots approached barely 10%.

For the loss of leaves, it was observed from the beginning of November (autumn) with a percentage of fall less than 10%, reaching a maximum of the order of 75 to

95% in the middle of winter (between February and March), with the exception of *H. parvifolia*, which did not show a significant loss of leaves during the winter, for its peak recorded at only 25%. From there, it can be seen that this last species did not completely lose its leaves at any time of the year, nor does it completely renew them.

All the species presented a gradual replacement of leaves at the different seasons of the year of study, and mature leaves were maintained for most of the year. *Helietta parvifolia* never lacked mature leaves, while the other species, after the peak recorded at 100% at the end of October (autumn), showed a remarkable decrease up to 15, 10, 5, and 0% for *A. berlandieri*, *E. Ebano*, *A. wrightii*, and *H. pallens*, respectively, in the winter period.

6.1.2 Flowering

The floral development was irregular in quantitative terms and recorded an annual periodicity in which four events were observed (Fig. 1.41), with significant statistical differences ($P < 0.05$) among species. The button formation stage was the longest, beginning in the month of May and ending in November, except for *A. wrightii*

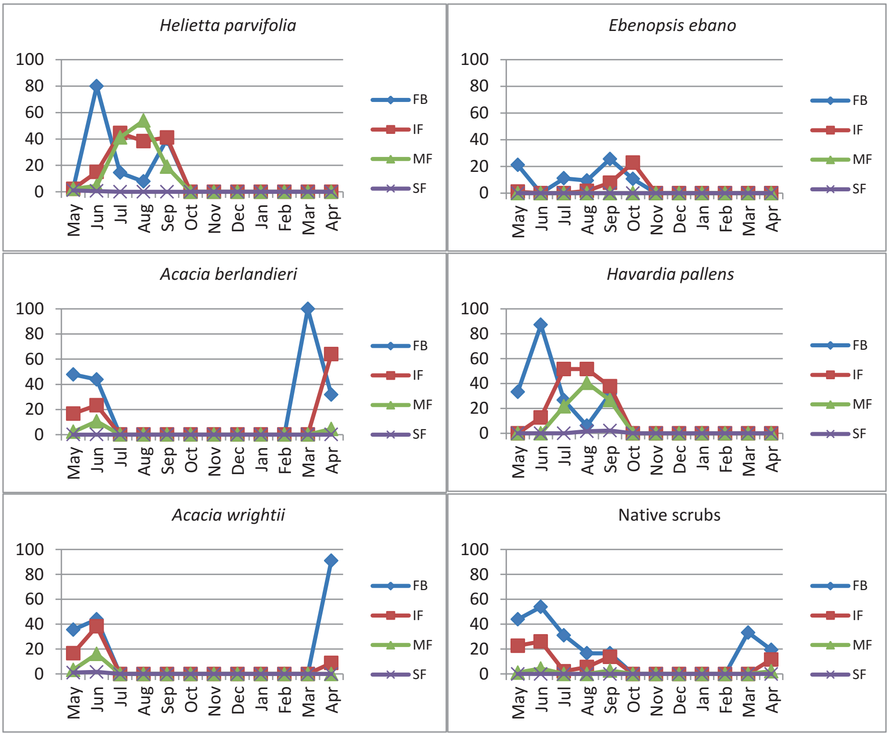


Fig. 1.41 Production of flowers in five species of the Tamaulipan thorn scrub from May 2013 to April 2014. *FB* floral buds, *IF* immature flowers, *MF* mature flowers, *SF* senile flower

where it was from May to July. *Helietta parvifolia* and *Havardia pallens* showed the maximum peaks in the month of June (spring), at the percentage values of 80% and 90%, respectively. In the area of native vegetation, the peak of presence of flower buds was registered until September (in spring and summer), at 50%.

These buttons matured gradually, with a behavior peculiar to each species. Duration and intensity of immature flowers were higher in *H. parvifolia* and *H. pallens* (from mid-May to October, with peaks at 45% and 55%, respectively, corresponding to late spring up to early autumn). The lowest duration of immature flowers was recorded in *A. berlandieri* and *A. wrightii* (May to July), at 25% and 39% intensity, respectively. The immature flowers took longer to appear in *E. ebano*, presenting in August (midsummer), as well as mature flowers, which were observed until October (autumn), with an intensity of 35%.

The flower maturation period was very short in *A. berlandieri* and *A. wrightii*, with low intensities (15% and 30%, respectively), whereas it was more prolonged in *H. parvifolia* and *H. pallens* with two peaks at 70% in August and 65% in September for *H. parvifolia* and 65% in August and 35% in September for *H. pallens*, being the summer for that phenological phase.

It may be appreciated that the process of floral maturation is slower in *E. ebano* than in the other species, which maturated simultaneously. In native vegetation, there was a successive sequence in terms of duration and intensity, with the appearance of buds in May (20%), immature flowers in June (10%), and mature flowers in August (8%).

No senile flowers were recorded in *E. ebano* and *A. berlandieri*. As for *H. parvifolia* and *H. pallens*, the flowers fell until October (autumn), registering percentages of 25 and 65% of senile flowers, respectively. The lowest value was recorded with *A. wrightii* (5%) in the month of June (spring).

For experimental plantations, two main functional groups of species can be identified according to their flowering during the study period: the first one consists of two species with a single event (*E. ebano* and *H. pallens*) and the second with three species (*H. parvifolia*, *A. berlandieri*, and *A. wrightii*), which presented more than one event. The native vegetation area is classified in this second group.

6.1.3 Fruiting

Event following the flowering, the fruiting varied, based on the species (Fig. 1.42). There were highly significant differences ($P < 0.001$) among species and by plant formation. No fruits were observed in *E. ebano* due to the floral abortion events that occurred in this species. For *A. berlandieri*, a low percentage of immature fruits (10%) was observed at the end of spring (July), which could not mature, and fell immediately.

The fruiting process was positively distinguished in the other species, with four well-defined stages. The first one started in June and was maintained until October for *H. parvifolia*, with the development of embryonic fruits, which reached maturity in the months of October to March, presenting as the species with the longest

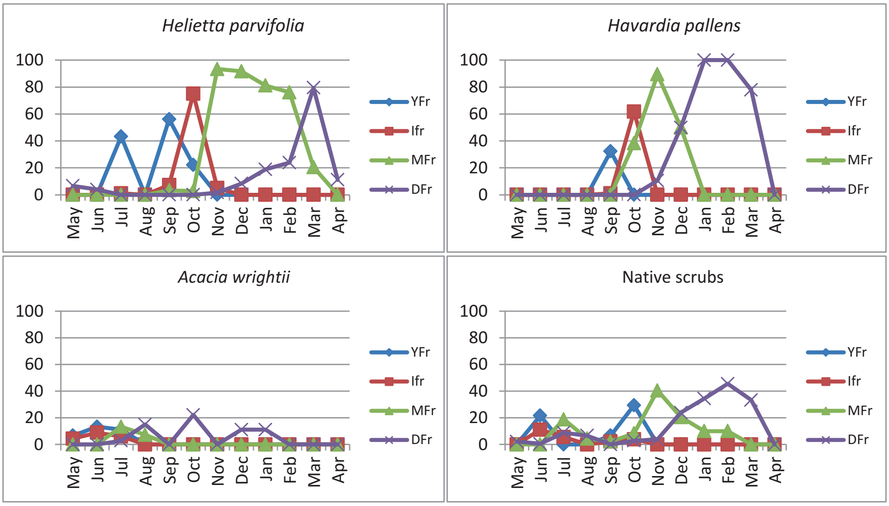


Fig. 1.42 Phenogram of fruiting in the Tamaulipan thorn scrub species, from May 2013 to April 2014. *YFr* young fruits, *IFr* immature fruits, *MFr* mature fruits, *DFr* Dehiscent fruits

duration of mature fruits, as well as greater intensity (>95% between November and December). These fruits reached their peak of maturity during the month of December (autumn), and they began directly the dispersion of seeds prolonging this stage until April (beginning of spring), registering the maximum dispersion in March (end of winter).

The fruiting of *H. pallens* began in the full summer, with a low percentage of young flowers reaching their maximum in September (35%), which began to mature, reaching full maturity at the end of October (95%), and initiating the dispersion at the same time. The fruit dispersion phase was concluded until the month of April, being the stage with greater duration and intensity.

A similar behavior was observed in the native Scrubland, but with lower intensity (20%, 45%, and 55% of embryonic fruits, mature fruits, and fruits in dispersion, respectively). However, additional fructification was recorded in May, but not more than 10%, of which 5% matured before falling in July. In most cases, the duration of the phases of embryonic to immature fruits is relatively brief, covering in about 2 weeks. As for the fruit maturation, it appeared between 4 and 6 weeks after the beginning of the fruiting. However, seed dispersal was slow, taking several months.

6.2 Forest Production

The evaluation of forest potential was realized through the determination of dasometric values, as observed in Table 1.7.

Table 1.7 Dasometric values (± standard deviation) of five timber species of the Tamaulipan thorn scrub in Northeastern Mexico

Species	Sites	No of shoots	Total height (m)	BD (cm)	DBH (cm)	*V* (m³/ha/year)
Helietta parvifolia	PE	7.56 ± 0.38	4.94 ± 0.13	4.53 ± 0.34	3.05 ± 0.28	0.396 ± 0.03
	NS	2.96 ± 0.44	4.88 ± 0.15	4.69 ± 0.39	3.51 ± 0.32	0.068 ± 0.04
Ebenopsis ebano	PE	3.28 ± 0.36	4.70 ± 0.12	7.73 ± 0.32	5.79 ± 0.26	0.118 ± 0.03
	NS	2.69 ± 0.83	5.74 ± 0.28	12.84 ± 0.74	9.68 ± 0.61	0.377 ± 0.07
Acacia berlandieri	PE	7.78 ± 0.36	3.29 ± 0.12	3.18 ± 0.32	2.21 ± 0.26	0.052 ± 0.03
	NS	5.52 ± 0.65	3.49 ± 0.22	2.35 ± 0.58	1.74 ± 0.48	0.029 ± 0.01
Havardia pallens	PE	3.49 ± 0.35	4.72 ± 0.12	5.21 ± 0.31	3.84 ± 0.26	0.059 ± 0.03
	NS	3.26 ± 0.45	3.65 ± 0.15	3.55 ± 0.41	2.50 ± 0.33	0.022 ± 0.04
Acacia wrightii	PE	2.02 ± 0.39	3.57 ± 0.13	7.48 ± 0.35	4.25 ± 0.29	0.061 ± 0.04
	NS	1.36 ± 0.89	4.32 ± 0.30	10.23 ± 0.80	7.84 ± 0.66	0.211 ± 0.08

BD basal diameter, *DBH* diameter at breast height, *V* volume, *PE* experimental plantation, *NS* native scrub

Table 1.8 Analysis of variance of the shoot number/tree in the two sites

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	4741.046	1	4741.046	533.987	0.000
Site	206.907	1	206.907	23.304	0.000
Species	875.159	4	218.790	24.642	0.000
Site * species	303.467	4	75.867	8.545	0.000

6.2.1 Number of Shoots

The capacity to produce shoots is considered as the main development mode of the scrubs, to establish and maintain after each cut and/or damage by frost, drought, fire, etc. Table 1.8 shows that there are highly significant differences ($P < 0.01$) among sites, species, and also their interactions (sites × species).

The highest numbers of shoots were recorded by the species *Acacia berlandieri* and *Helietta parvifolia*, with an average of 7.78 and 7.56 shoots per tree, respectively (Table 1.7), in experimental plantations. On the other hand, *Acacia wrightii* almost did not develop shoots, presenting generally only one stem. A similar development was recorded with *Ebenopsis ebano*, since it had a main stem of good size and vigor, whereas the shoot, when it existed, was nothing compared to the main stem. As for *Havardia pallens*, a constant number of shoots (three shoots/tree) was recorded, both in the native scrub and in the experimental plantations.

6.2.2 Total Height

There is a highly significant difference ($P < 0.01$) in the total height of the trees among species, as shown in Table 1.9. However, there was no significant difference ($P > 0.05$) among sites.

Table 1.9 Analysis of variance of the total height

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	5582.151	1	5582.151	5493.963	0.000
Site	2.391	1	2.391	2.353	0.126
Species	136.874	4	34.218	33.678	0.000
Site * species	48.936	4	12.234	12.041	0.000

Table 1.10 Analysis of variance of the basal diameter (BD) of the species

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	11,355.280	1	11,355.280	108.469	0.000
Site	90.899	1	90.899	12.812	0.000
Species	2110.337	4	527.584	74.361	0.000
Site * species	433.875	4	108.469	15.288	0.000

Table 1.11 Analysis of variance of the diameter at breast height (DBH) of the species

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	5866.758	1	5866.758	1224.739	0.000
Site	111.279	1	111.279	23.231	0.000
Species	1149.875	4	287.469	60.012	0.000
Site * species	321.523	4	80.381	16.780	0.000

The total height oscillated between 3.29 and 4.94 m in experimental plantations, while in the native scrub, it varied from 3.49 to 5.74 m (Table 1.7). In both sites, *E. ebano* and *H. parvifolia* presented the highest height, with 5.24 and 4.90 m, respectively, while *A. berlandieri* recorded the lowest height, 3.29 and 3.49 m in plantations and in the native area, respectively.

6.2.3 Basal Diameter (BD) and Diameter at Breast Height (DBH)

Tables 1.10 and 1.11 show the existence of highly significant differences ($P < 0.01$) in basal diameter (BD) and diameter at breast height (DBH). The average basal diameter was 5.59 cm in plantations and 5.20 cm in native vegetation, while the diameter at breast height was 83 cm in plantations and 3.86 cm in native vegetation; *E. ebano* and *A. wrightii* exhibited greater diameter both in basal diameter and in diameter at breast height 12.84 and 10.23 cm (BD) and 9.68 and 7.84 cm (DBH), respectively (Table 1.7). The lowest diameters were registered in *A. berlandieri*, with values of 2.35 cm (BD) and 1.74 cm (DBH).

On the other hand, it can be observed in Table 1.7 that the species whose number of shoots was lower presented greater diameter, both basal diameter (BD) and diameter at breast height (DBH). This is observed in *E. ebano* and *A. wrightii*, which registered an average of three and two shoots/tree, with an average of 10 and 9 cm BD, respectively, and the DBH of 8 and 6 cm, respectively.

Table 1.12 Analysis of variance of the useable wood volume

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	5.752	1	5.752	80.414	0.000
Site	0.001	1	0.001	0.019	0.890
Species	3.089	4	0.772	10.795	0.000
Site * species	3.451	4	0.863	12.063	0.000

Table 1.13 Analysis of variance of the species coverage by site

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	21,215.746	1	21,215.746	542.555	0.000
Site	1307.468	1	1307.468	33.436	0.000
Species	3798.215	4	949.554	24.283	0.000
Site * species	4237.175	4	1059.294	27.090	0.000

6.2.4 Volume of Wood

The volume of wood did not show statistical difference ($P > 0.05$) among sites; however, there were highly significant differences ($P < 0.01$) among species (Table 1.12). The greater volume was registered in *H. parvifolia* (0.396 m^3/ha/year) in experimental plantation and *E. ebano* (0.377 m^3/ha/year) in native scrub, while the lower production was registered with the species *H. pallens* (0.022 m^3/ha/year) and *A. berlandieri* (0.029 m^3/ha/year) in native vegetation (see Table 1.7).

The wood volume was greater in native site, compared to those in experimental plantation for the species *E. ebano* and *A. wrightii* with 0.377 against 0.118 m^3/ha/year and 0.211 against 0.061 m^3/ha/year, respectively.

6.3 Fodder Production

The evaluation of forage potential was realized through the determination of canopy coverage that represents the size and/or foliar density of tree-shrub strata, leaf biomass of each of the species, and the litterfall that constitutes the leaf material lost after falling, but which contributes later to supply organic matter and nutrients to the trees. In this section, the herbaceous stratum is of great importance, so that its quantification and characterization were also performed.

6.3.1 Canopy Coverage of the Tamaulipan Thorn Scrub Species

The analysis of variance indicates highly significant differences ($P < 0.01$) among species, among sites, and also among their interactions of species * sites (Table 1.13).

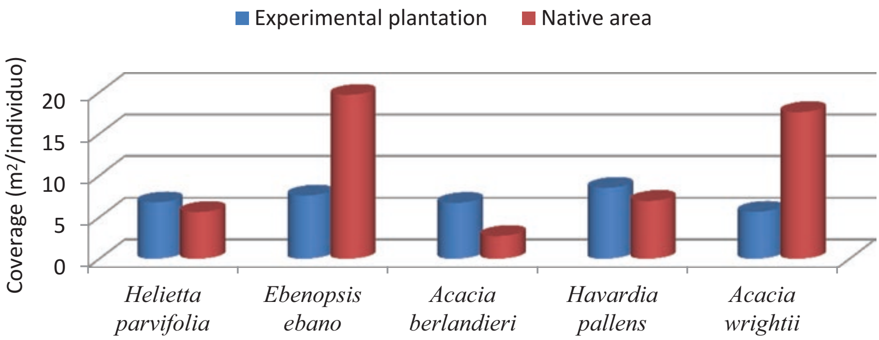


Fig. 1.43 Coverage of shrub and arboreal species of the Tamaulipan thorn scrub in experimental plantations and in native area

Table 1.14 Analysis of variance for leaf biomass

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	4.99701E7	4	1.24925E7	6.39	0.0003
Species	5.51028E7	3	1.83676E7	9.40	0.0000
Residual	1.01584E8	52	1.95354E6		
Total (corrected)	2.06657E8	59			

The individuals of the species *E. ebano* and *A. wrightii* presented very high values of coverage in native vegetation. The areas occupied by their crowns were 19.68 and 17.6 m^2/individuals, respectively (Fig. 1.43). The individuals of the species *H. pallens*, *H. parvifolia*, and *A. berlandieri* covered greater area in plantations (8.53, 6.78, and 6.72 m^2/individual, respectively), compared with the native vegetation (6.96, 5.62, and 2.73 m^2/individual, respectively). The lower coverage (2.73 m^2/individual) was presented by *A. berlandieri*, in the native scrub.

6.3.2 Leaf Biomass

A highly significant difference ($P < 0.01$) was observed in leaf biomass production among species and among seasons (Table 1.14). The average annual production was greater in *E. ebano* with 2686.80 kg ha^{-1} and lower in *A. wrightii*, with 431.21 kg ha^{-1} (Fig. 1.44).

The leaf biomass reached the maximum of its productivity in summer, with a very high value (9029.32 kg ha^{-1}) in *E. ebano*, while the lower value (103.08 kg ha^{-1}) was registered in *A. wrightii* in winter (Fig. 1.45).

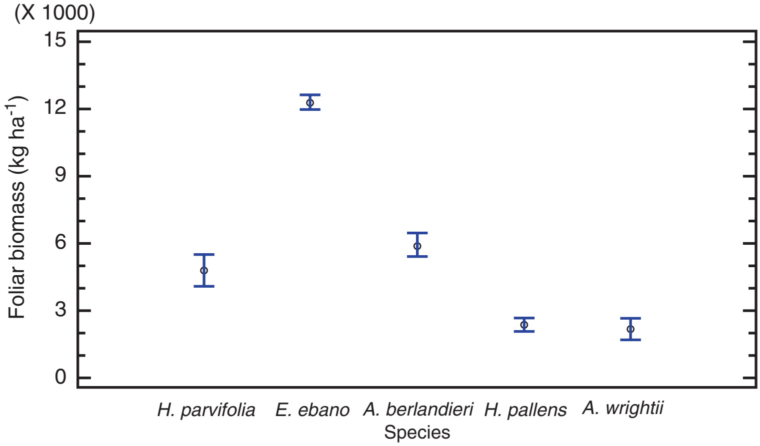


Fig. 1.44 Annual average of leaf biomass production (kg ha^{-1}) of five species of the Tamaulipan thorn scrub

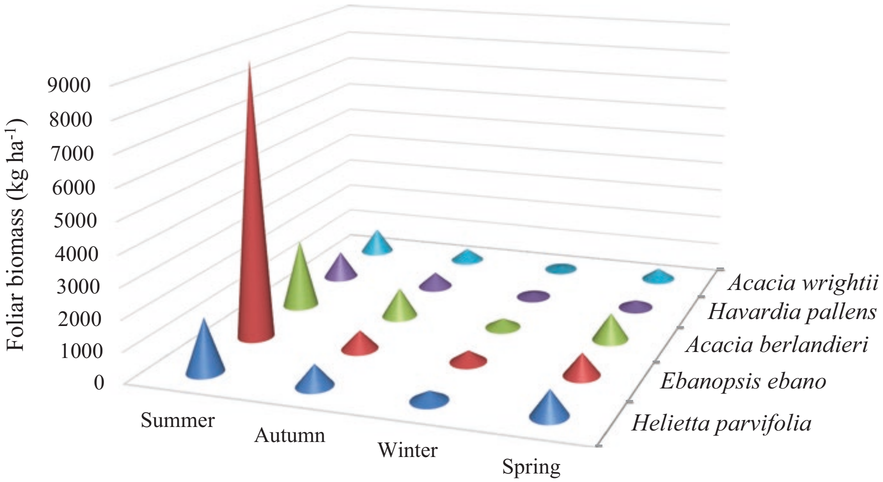


Fig. 1.45 Seasonal leaf biomass production (kg ha^{-1}) of five species of the Tamaulipan thorn scrub in experimental plantations

6.3.3 Production of Litterfall

All the species presented similar pattern in the production of litterfall during the period of study (Fig. 1.46). There were no statistically significant differences ($P > 0.05$) among species (Table 1.15). However, highly significant differences were observed among seasons of a year ($P < 0.01$).

The average annual production varied between 159.87 and 180.33 kg ha^{-1}, values corresponding, respectively, to *E. ebano* and *A. wrightii* (Fig. 1.47).

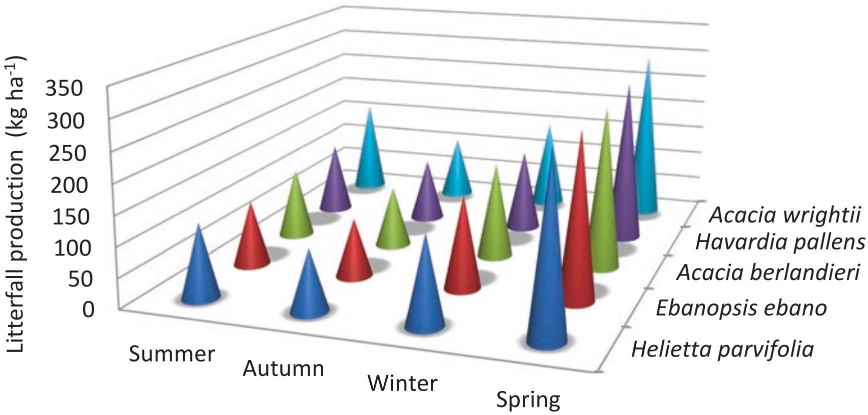


Fig. 1.46 Seasonal rate of litterfall (kg ha^{-1}) and its standard deviation in experimental plantations of five species of the Tamaulipan thorn scrub

Table 1.15 Analysis of variance for litterfall by species and season of the year

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	2894.58	4	723.644	0.90	0.4707
Species	292,499	3	97,499.7	121.29	0.0000
Residual	41,800.2	52	803.85		
Total (corrected)	337,194	59			

6.3.4 Herbaceous Production

The analysis of variance (Table 1.16) indicates that no significant differences were observed in the biomass production of the herbaceous species in both sites ($P = 0.358$); however, highly significant differences ($P < 0.01$) were found in the biomass production of herbaceous species present under shrubs, among seasons. This biomass in winter presented lower production of herbaceous, with values between 0.08 and 0.18 kg ha^{-1} year^{-1} in experimental plantations and 0.07 and 0.22 kg ha^{-1} year^{-1} in native vegetation. The highest values were recorded in spring for *A. berlandieri* (0.27 kg ha^{-1} year^{-1}) and *H. pallens* (0.25 kg ha^{-1} year^{-1}) in the native scrub and in autumn for *A. wrightii* (kg ha^{-1} year^{-1}) in experimental plantations (Fig. 1.48).

6.3.5 Characterization of Herbaceous Species

Table 1.17 shows the species found in the low stratum, which is considered as a potential forage resource, depending on its importance per shrub species and per site.

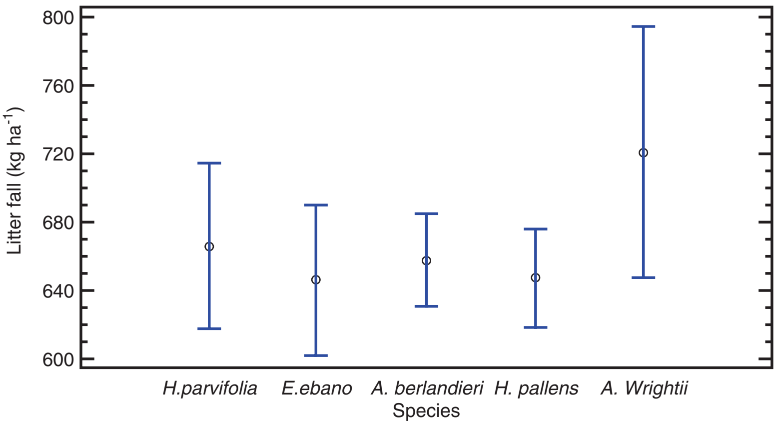


Fig. 1.47 Annual deposition of litterfall (kg ha^{-1}) in experimental plantations of five species of the Tamaulipan thorn scrub

Table 1.16 Analysis of variance of herbaceous biomass under shrubs by site

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Intersection	1.542	1	1.542	291.856	0.000
Site	0.005	1	0.005	0.856	0.358
Species	0.160	4	0.040	7.559	0.000
Site * species	0.085	4	0.021	4.017	0.005

The inventory of the Tamaulipan thorn scrub herbaceous plants at both sites shows the presence of approximately 80 species, belonging to 15 different families. This inventory reveals that several herbaceous species are found under almost all shrub species of the Tamaulipan thorn scrub. *Lantana sp*. and *Stipa lessingiana* (grass) were the most common species; these two herbaceous species proved to be the most important species, demonstrating their high capacity to withstand drastic conditions that may prevail under shrubs.

In terms of specific richness, the *A. wrightii* plantation proved to be the richest in biodiversity ($N = 30$), while in native scrubland, *A. berlandieri* was characterized by a marked poverty in terms of low stratum biodiversity, presenting $N = 7$.

6.4 Bioenergy Characteristics and Chemical Composition

6.4.1 Charcoal Production

The yield of charcoal showed significant differences ($P < 0.05$) among species (Table 1.18); however, the different plant components (trunk, branches) presented similar results ($P > 0.05$).

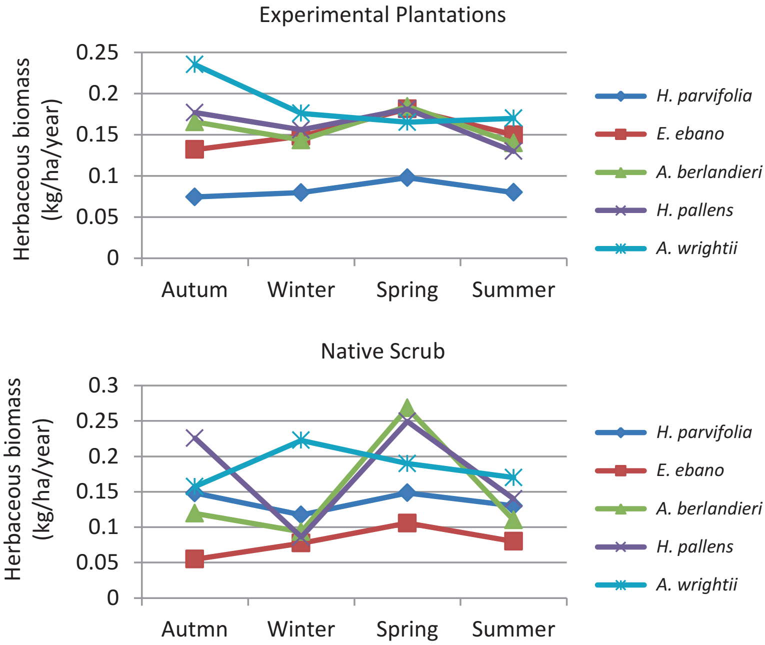


Fig. 1.48 Annual herbaceous biomass under five tree-shrub species of the Tamaulipan thorn scrub in two sites

The values oscillated between 20 and 30%, with the highest percentage corresponding to *A. wrightii* with 30% of charcoal produced by its trunk, and the lowest percentage was presented by *H. parvifolia* with 19.94% of charcoal produced by its branches (Fig. 1.49).

6.4.2 Biofuel Quality

The biofuel quality of the studied biomass was evaluated through the immediate analyses, which consisted of determining the moisture, volatile, ash, and fixed carbon contents.

6.4.2.1 Moisture Content

The analysis of variance (Table 1.19) showed highly significant differences ($P < 0.01$) among species, while the components did not show significant difference ($P > 0.05$).

The moisture content ranged from 6.88 to 12.22% for wood samples (Fig. 1.50a), while charcoal ranged from 4.25 to 4.9% (Fig. 1.50b), with the highest moisture content (4.9%), both in trunk and branches of the species *H. parvifolia*, *A. wrightii*,

Table 1.17 Importance value of herbaceous vegetation under five shrub and arboreal species of the Tamaulipan thorn scrub in experimental plantations and native area

	Importance value (%)									
	Helietta parvifolia		*Ebenopsis ebano*		*Acacia berlandieri*		*Havardia pallens*		*Acacia wrightii*	
Herbaceous species	EP	NS	EP	NS	EP	NS	EP	NS	EP	NS
Lantana sp. (Verbenaceae)	18.23	23.74	15.18	10.36	18.78	19.02	19.57	18.54	16.18	12.94
Stipa lessingiana (Poaceae)	9.60	2.59	5.51	2.84	4.20	3.12	6.81	4.30	5.13	21.88
Malpighia glabra (Malpighiaceae)	5.23		5.48	2.84	13.08		6.35	1.99	24.28	1.82
Meximalva filipes (Malvaceae)	3.95						2.49			
Croton cortesianus (Euphorbiaceae)	3.72	9.32	9.78	4.73	3.03		4.03	6.73	8.64	4.66
Justicia pilosella (Acanthaceae)	3.69		1.18				2.55			
Parthenium fruticosum (Asteraceae)	3.61		2.43	5.06			5.75			
Ruellia occidentalis (Acanthaceae)	3.57		1.80	4.95	3.03		4.15			
Karwinskia humboldtiana	3.57	3.83	5.16		2.71	2.94		1.36		2.65
Evolvulus alsinoides (Convolvulaceae)	3.52		13.02				1.12			
Eysenhardtia polystachya (Fabaceae)	3.44	2.20			1.35		4.47	1.36	1.15	1.26
Forestiera angustifolia (Oleaceae)	3.19							1.36		1.26
Hibiscus cardiophyllus	2.84				3.39		2.40			

Senna greggii (Fabaceae)	2.75						1.12			
Acacia berlandieri (Fabaceae)	2.46				8.07	3.74	1.76	1.36	1.15	
Acacia rigidula (Fabaceae)	1.70						1.12			
Scutellaria sp. (Lamiaceae)	1.23	4.59		3.15			5.75			
Urvillea ulmacea (Sapindaceae)	1.70	1.49		2.26	3.39		3.18			
Cyphomeris gypsophiloides (Nyctaginaceae)	1.23						4.31			
Havardia pallens	1.47						1.91			1.82
Zexmenia hispida	1.23						5.11			
Elytraria bromoides (Acanthaceae)	1.99		4.54				3.34			
Leucaena sp. (Fabaceae)	1.23								1.15	
Helietta parvifolia (Rutaceae)	1.23	3.69							1.67	
Randia rhagocarpa (Rubiaceae)		2.20	1.18	2.22				3.67	1.15	2.65
Lantana velutina (Verbenaceae)		6.10								
Salvia ballotiflora (Lamiaceae)		6.89						1.36	1.15	
Fraxinus greggii (Oleaceae)		1.49		2.30						

(continued)

Table 1.17 (continued)

	Importance value (%)									
	Helietta parvifolia		*Ebenopsis ebano*		*Acacia berlandieri*		*Havardia pallens*		*Acacia wrightii*	
Herbaceous species	EP	NS	EP	NS	EP	NS	EP	NS	EP	NS
Phyllanthus polygonoides (Euphorbiaceae)		4.21		1.36						
Diospyros texana (Ebenaceae)		3.05							1.15	4.07
Caesalpinia mexicana (Fabaceae)			1.18	1.36						
Zanthoxylum fagara (Rutaceae)			1.18	2.26	4.56		2.86	1.36	2.70	1.26
Ebenopsis ebano (Fabaceae)			1.18							
Ibervillea tenuisecta (Cucurbitaceae)			1.18		1.35	2.12				
Bernardia myricifolia (Euphorbiaceae)				3.58				1.36		1.26
Bastardia viscosa (Malvaceae)				4.28						
Amyris texana (Rutaceae)				2.26						1.26
Mimosa malacophylla				1.36						1.26
Porlieria angustifolia (Zygophyllaceae)				1.36						
Justicia turneri (Acanthaceae)				4.99						
Ipomoea sp.				1.36				2.61		

Aloysia lycioides (Verbenaceae)				2.26						
Solanum triquetrum				3.11						
Viguiera stenoloba (Asteraceae)							4.15			
Cynanchum barbigerum (Asclepiadaceae)							1.12			
Cissus incisa							2.40			
Capsicum annum (Solanaceae)									1.67	
Chromolaena odorata (Asteraceae)									1.15	
Celtis pallida (Ulmaceae)									1.15	
Acacia wrightii									2.18	
Total	24	14	16	22	12	5	24	13	16	14

EP experimental plantation, *NS* native scrub

Table 1.18 Analysis of variance of yield in charcoal by species and plant components

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Species	639.096	4	159.774	3.34	0.0138
Components	50.4094	1	50.4094	1.05	0.3079
Residuals	4024.06	84	47.9055		
Total (corrected)	4713.57	89			

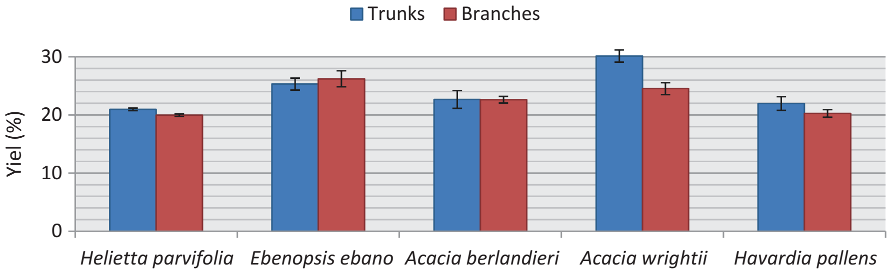


Fig. 1.49 Yield in charcoal production of five species of the Tamaulipan thorn scrub

Table 1.19 Analysis of variance of moisture content by species and plant components

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	0.0045334	1	0.0045334	0.05	0.8252
Species	6.67996	4	1.66999	18.07	0.0000
Residual	7.76155	84	0.0923994		
Total (corrected)	14.446	89			

and *A. berlandieri*. The lowest moisture content was produced by *E. ebano* and *H. pallens* with 4.26% in the trunk of the two species and 4.25% and 4.41% in branches, respectively.

6.4.2.2 Volatile Materials

There were significant differences ($P < 0.05$) among the components of tree and highly significant differences ($P < 0.01$) among the species studied (Table 1.20).

The values of volatile matter fluctuated between 73.35 and 82.30% for the sample of wood (Fig. 1.50a); the highest content was recorded by the branches of *H. pallens* and the smaller content by the trunk of *E. ebano*. For charcoal, the values ranged from 12.29 to 22.28% (Fig. 1.50b), with the highest content corresponding to *A. berlandieri*, both in branches (22.28%) and in the trunk (17.51%), and the lowest content (12.29%) to branches of *H. parvifolia*.

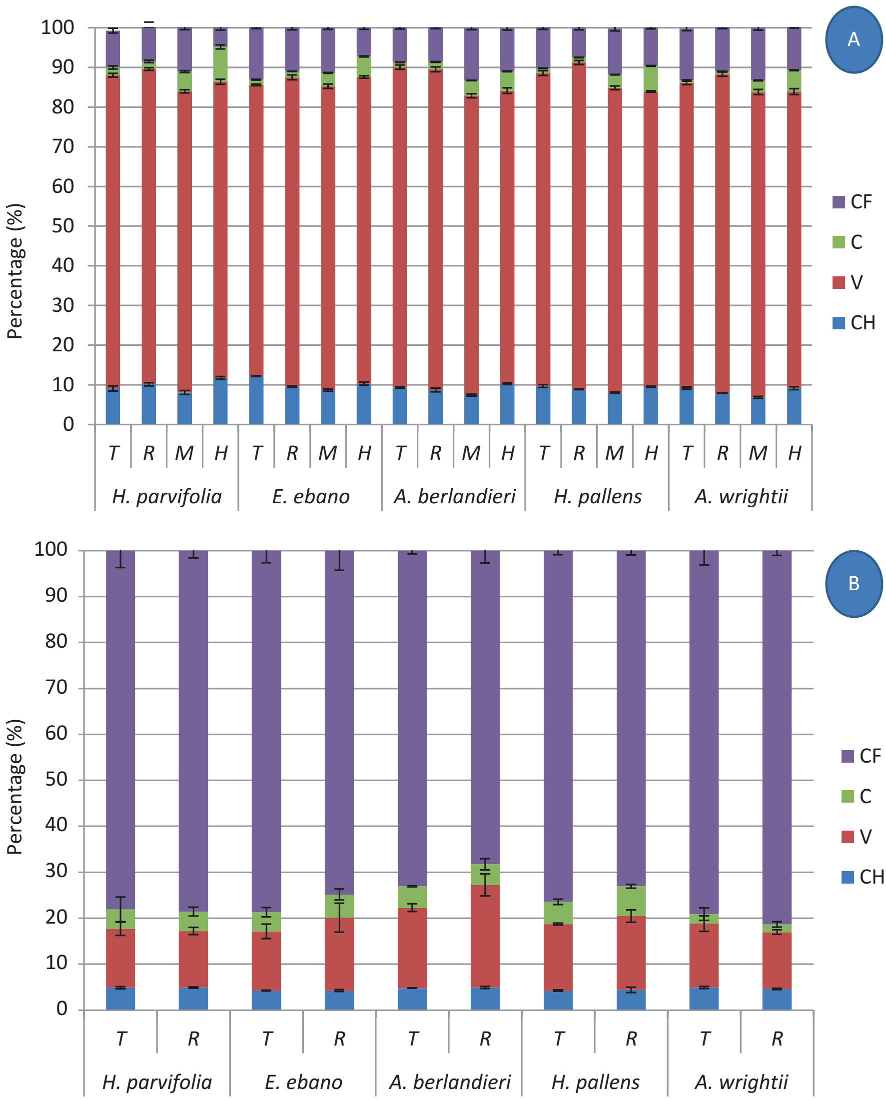


Fig. 1.50 Physicochemical properties of wood (**a**) and charcoal (**b**) of native species of the Tamaulipan thorn scrub in different components. *CH* moisture content, *V* volatile materials, *C* ash, *CF* fixed carbon, *T* trunk, *R* branches, *M* twigs, *H* leaves

6.4.2.3 Ash Content

The species showed highly significant differences ($P < 0.01$), while no significant differences were found among plant components ($P > 0.05$), as shown in Table 1.21.

The ash contents varied between 0.66 and 8.79% for the wood samples (Fig. 1.50a), with the lowest values (0.66 and 0.67%) corresponding to the trunks

Table 1.20 Analysis of variance for the volatile matter content in trunk, branches, twigs, and leaves of five forest species in Linares, N.L.

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	47.3774	1	47.3774	8.25	0.0052
Species	610.699	4	152.675	26.59	0.0000
Residual	482.384	84	5.74267		
Total (corrected)	1140.46	89			

Table 1.21 Analysis of variance for ashes by species and their components (trunk, branches, twigs, and leaves)

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	3.56903	1	3.56903	1.92	0.1698
Species	141.638	4	35.4094	19.03	0.0000
Residual	156.337	84	1.86116		
Total (corrected)	301.544	89			

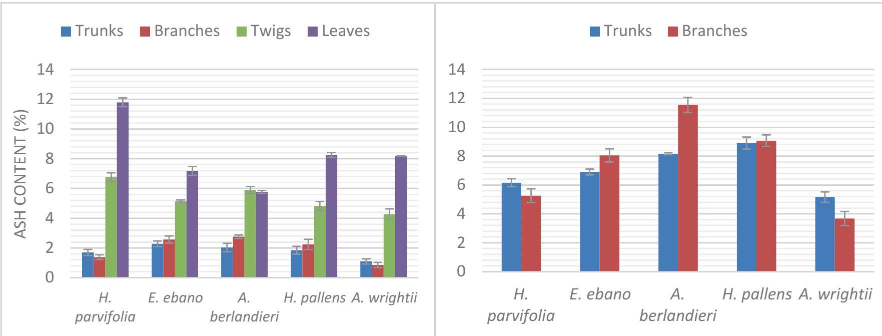


Fig. 1.51 Ash content obtained according to ISO 17 225-2

and branches of *A. wrightii*, respectively, and the highest values corresponding to the leaves of *H. parvifolia*. The highest values were recorded on the leaves of all species, followed by the twigs, which supports the idea of a demineralization of the trunk toward the leaves.

With respect to charcoal, the rank obtained was 1.68–6.49% (Fig. 1.50b), values presented by the branches of *A. wrightii* and *H. pallens*, respectively, with highly significant differences ($P < 0.01$) between species.

These results show the same trend as the ash content results obtained according to ISO 17 225-2. All the species showed a similar pattern: trunk <branches <twigs <leaves, with variations from 1.09 to 2.29% in trunks, 0.86 to 2.75% in branches, 4.26 to 6.76% in twigs, 5.77 to 11.79% in leaves for wood samples, 5.16 to 8.91 in trunks, and 3.68 to 11.54 in branches for charcoal (Fig. 1.51). This result indicates that the ash content is higher in charcoal than in biomass.

Table 1.22 Analysis of variance for fixed carbon by species and their components

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	78.1393	1	78.1393	7.95	0.0060
Species	966.32	4	241.58	24.57	0.0000
Residual	825.75	84	9.83036		
Total (corrected)	1870.21	89			

Table 1.23 Analysis of variance for calorific value by species and their components

Source of variation	Sum of squares	Df	Quadratic mean	*F*	*P*
Components	3.82691E6	1	3.82691E6	6.52	0.0125
Species	5.09455E7	4	1.27364E7	21.69	0.0000
Residual	4.93168E7	84	587105		
Total (corrected)	1.04089E8	89			

The analysis of variance showed highly significant differences ($P < 0.001$) among species and among components of trees (trunk, branches, twigs, and leaves), which indicate the variation of inorganic substances and function of the components of trees and by species.

The lowest values were recorded in *A. wrightii* trunk (1.09%) and branches (0.86%), while the highest percentage of ash was found in leaves of *H. parvifolia*.

6.4.2.4 Fixed Carbon

With reference to fixed carbon, the differences were highly significant ($P < 0.01$) among species and significant ($P < 0.05$) among the different components (Table 1.22).

The fixed carbon presented a range of 4.9–13.31% in biomass samples (Fig. 1.50a), with the lowest content corresponding to the leaves of *H. parvifolia* and the highest value to the trunk of *E. ebano* and twigs of *A. berlandieri* and *A. wrightii*. This range is much lower than the range of 68.26–81.34% recorded by charcoal, values corresponding to branches of *A. berlandieri* and *A. wrightii*, respectively (Fig. 1.50b).

6.4.2.5 Calorific Value

For the calorific value, highly significant differences ($P < 0.01$) among species were detected and significant differences ($P < 0.05$) among components of the tree (Table 1.23).

From the calculations made, the calorific values obtained were between 14.533 and 17.844 KJ kg^{-1} for the wood samples, being the highest calorific value registered in trunk of *A. wrightii* and the lowest in leaves of *H. parvifolia* (Fig. 1.52).

Fig. 1.52 Estimated calorific value of wood and charcoal of five species of the Tamaulipan thorn scrub in different components

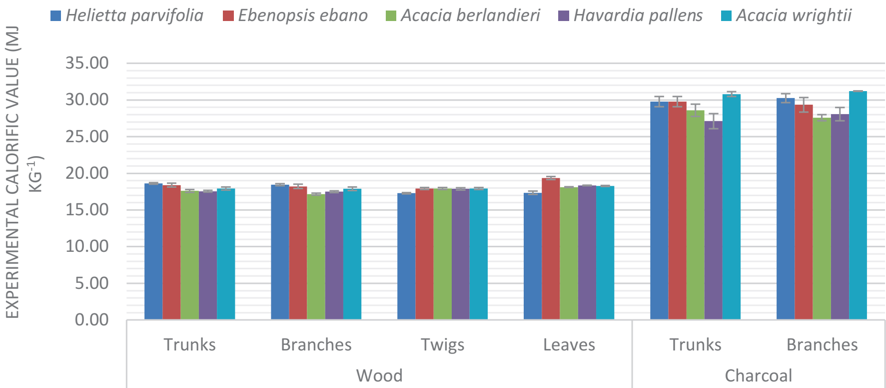


Fig. 1.53 Experimental calorific value of five species of the Tamaulipan thorn scrub in different components

For charcoal, the values obtained ranged from 28,000 to 30,932 KJ kg^{-1}, corresponding to the branches of *A. berlandieri* and *A. wrightii*, respectively (Fig. 1.52).

For the results of the determination through calorimetric pump, ranges of 27.12–31.20 MJ kg^{-1} and 17.15–19.36 MJ kg^{-1} were registered for charcoal and wood samples, respectively (Fig. 1.53). These experimental values correspond to the values obtained from the evaluation by calculation; therefore, the determination of calorific value through immediate analysis is considered as a method applicable in the Tamaulipan thorn scrub.

In all the cases, it is observed that the calorific value of charcoal is greater than that presented in biomass. The registered values oscillated between 27.12 and 30.80 MJ kg^{-1} in trunks, corresponding to *H. pallens* and *A. wrightii*, and between

27.59 and 31.20 MJ kg^{-1} in branches, corresponding to *A. berlandieri* and *A. wrightii*, respectively.

As for the wood samples, the calorific value is within the ranges of 17.56–18.61 MJ kg^{-1} for trunks and 17.15–18.45 MJ kg^{-1} for branches, being *H. parvifolia* the species with the highest value (18.61 MJ kg^{-1}), followed by *E. ebano* (18.40 MJ kg^{-1}) and *A. wrightii* (17.93 MJ kg^{-1}) for the trunks, and with the same pattern in branches (18.45, 18.22, and 17.90 MJ kg^{-1}, respectively). The lowest calorific value was presented by twigs and leaves (17.29 and 17.35 MJ kg^{-1}) of *H. parvifolia*. On the other hand, high values were observed in leaves of the other four species, which reached the maximum of 19.36 MJ kg^{-1} in *E. ebano*.

6.4.2.6 Relationship Between the Characteristics of Biofuels Tested

The fixed carbon proved to be the main component of charcoal, with a content of over 70%, while volatiles constitute the second main component of charcoal, with a percentage of more than 15%. This trend is reversed in the analyzed wood samples, where the largest component consists of volatiles, with contents higher than 70%, while fixed carbon is on a scale of 10%.

Table 1.24 reveals highly relationship ($P < 0.01$) among fixed carbon and volatiles, ash, and calorific value. There is a balance in the charcoal properties: charcoal with a lot of volatile materials and less fixed carbon burns more quickly, so you will have to use more charcoal, and if a charcoal has too much fixed carbon, it will have a higher ash content. Therefore, it is recommended to use a certain amount of charcoal with relatively fast ignition time and the other part of the charcoal with a shorter ignition time. This will ensure that at the time of igniting, the charcoal is easy to ignite and the other part more durable by the high percentage of fixed carbon. There are higher values of ash content in charcoal (5%) than in wood samples (<2%), for trunks and branches (Fig. 1.50a, b).

6.4.3 Inorganic Substances Obtained from Microanalysis of Ashes

Ash is the residue of combustion and consists mainly of inorganic elements. The X-ray spectroscopy showed a similar distribution of these elements in the studied species (Fig. 1.54), with a very high proportion of calcium (57.03–95.53%), followed by potassium (0.95–19.21%) and magnesium (0.88–13.47%).

Table 1.24 Matrix of correlations between variables determining the quality of biofuel

	Moisture	Volatiles	Ash	Fixed carbon	Calorific value
Moisture	1.0000	0.2355	0.3021	0.1807	0.1807
Volatiles		1.0000	0.0011	0.0000	0.0000
Ash			1.0000	0.0000	0.0000
Fixed carbon				1.0000	0.0000
Calorific value					1.0000

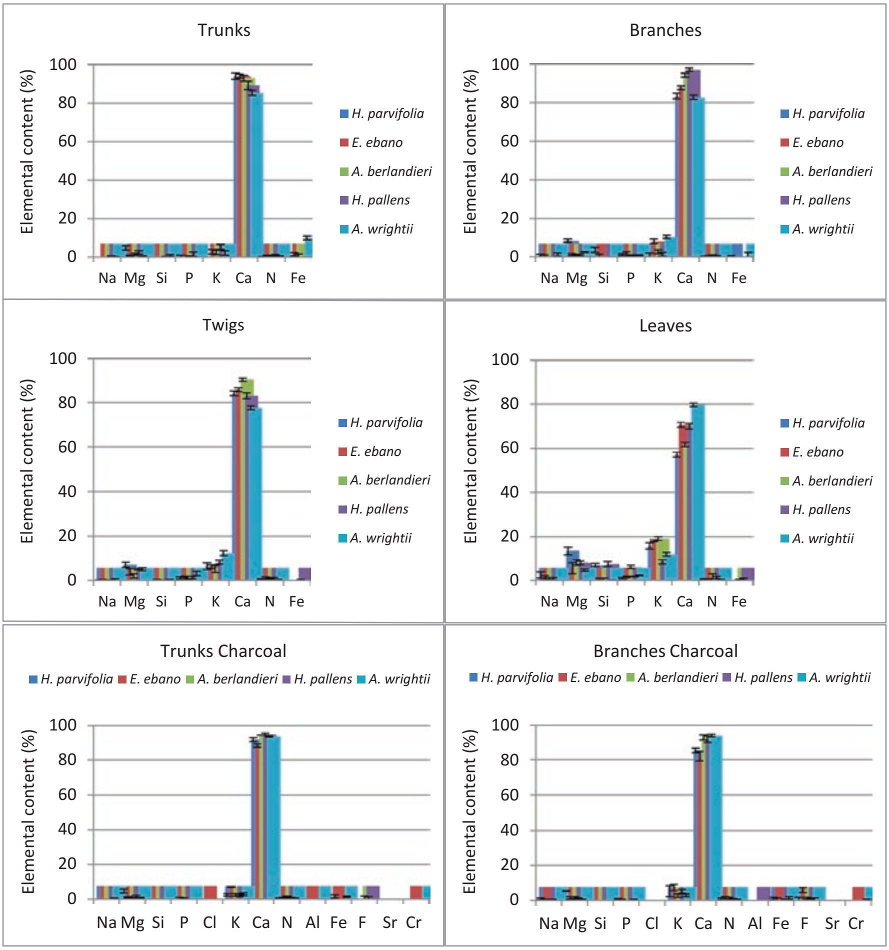


Fig. 1.54 Elemental content (%) of inorganic substances and standard deviation for the ash obtained from wood and charcoal of five timber species of the Tamaulipan thorn scrub in different components (trunks, branches, twigs, and leaves)

6.4.4 Chemical Elements (Contents of Carbon, Hydrogen, and Nitrogen) in Wood and Charcoal

The analysis of variance revealed significant differences ($P < 0.05$) in the values of chemical elements of wood, presenting carbon and hydrogen as the main elemental components of the forest biomass, with a constant trend for charcoal as well as for wood. Fluctuations were registered from 44.99 to 49.70% of C in flour of wood and leaves, 80.77 to 89.30% of C in charcoal, 5.89 to 6.62% of H in flour of wood and leaves, and 2.38 to 2.69 of H in charcoal (Fig. 1.55). These ranges indicate that much more carbon (C) is found in charcoal than in pure wood and, on the contrary,

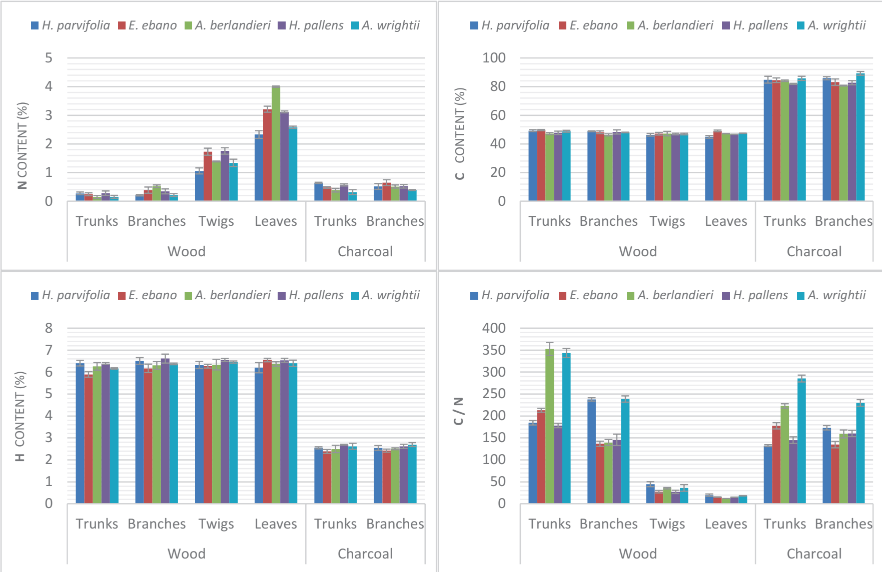


Fig. 1.55 Chemical elements in different components of five timber species of the Tamaulipan thorn scrub

more hydrogen (H) in wood than in charcoal. As for the nitrogen content, a great variation ($P < 0.001$) was observed, with respect to the different components and types of sample. The percentage sequence (2.33–4.0) > (1.06–1.76) > (0.21–0.52) > (0.15–0.28) was registered, corresponding to the flour samples for leaves > twigs > branches > trunks, respectively. Charcoal showed intervals of 0.39–0.65% and 0.32–0.64% of N for branches and trunks, respectively. Based on these results, it can be seen that the biomass also contains small proportions of nitrogen and that it is found in a greater proportion in charcoal than in wood. This trend is presented inversely, for the C/N ratio (Fig. 1.55).

6.4.5 Wood Chemical Components

The wood species are distinguished by the concentration of their constituent chemical components such as cellulose, hemicellulose, and lignin and by their density. Table 1.25 shows the averages and standard deviation of the chemical components for each species studied, in its different plant components.

6.4.5.1 Extractable Substances

The extractables varied significantly ($P < 0.05$) both among species and plant components, with ranges 11.98–38.12% in trunks, 9.16–19.37% in branches, and 22.01–31.81% in twigs (Table 1.25).

Table 1.25 Chemical components and standard deviation of five timber species of the Tamaulipan thorn scrub in different vegetal components (*T* trunk, *B* branches, *M* twigs)

Species	Vegetal component	Extractables[a]	Lignin[b]	Holocellulose[b]
Helietta parvifolia	T	14.56 ± 1.08	35.94 ± 1.01	47.8 ± 0.90
	B	10.38 ± 0.97	31.39 ± 0.61	56.85 ± 0.65
	M	32.08 ± 0.52	20.61 ± 0.37	40.55 ± 0.80
Ebenopsis ebano	T	38.12 ± 1.05	35.43 ± 0.20	24.17 ± 0.58
	B	11.99 ± 2.13	28.08 ± 0.34	67.36 ± 0.97
	M	24.95 ± 0.48	29.92 ± 0.59	49.99 ± 0.52
Acacia berlandieri	T	11.97 ± 0.27	28.78 ± 0.54	57.22 ± 0.47
	B	9.16 ± 1.99	21.04 ± 1.68	67.05 ± 1.73
	M	30.48 ± 0.18	26.56 ± 0.30	37.07 ± 0.67
Havardia pallens	T	12.10 ± 1.94	32.21 ± 0.69	53.84 ± 1.03
	B	10.99 ± 1.42	20.18 ± 1.39	66.49 ± 1.15
	M	31.81 ± 1.06	28.51 ± 0.25	34.86 ± 0.68
Acacia wrightii	T	26.84 ± 1.29	33.94 ± 2.67	38.13 ± 1.45
	B	19.37 ± 0.11	17.14 ± 1.48	62.63 ± 0.62
	M	22.01 ± 0.43	29.04 ± 0.88	44.69 ± 0.69
P		0.019*	0.014*	

[a]Components in percentage, based on the dry weight of the original sample
[b]Components in percentage, based on the dry weight of the samples free of extractables, *P* (*): significance at 5%

In all species, the following sequential pattern can be observed: methanol > hot water > acetone > cyclohexane, according to a gradient of decreasing yield of the total extractables (Fig. 1.56). The lowest amount of extractables was obtained with cyclohexane, ranging from 1.03 to 1.33% ($P = 0.0581$), followed by those obtained with hot water, methanol, and acetone. On the one hand, significant differences were found in the content of extractables soluble in acetone and methanol present in the different components; on the other hand, there were differences in the content of extractables soluble in hot water in the four types of materials.

It is observed in Fig. 1.56, the solubility of extractables registered in the solvents utilized, where it is observed the maximum solubility in methanol, with greater proportions of extractables in twigs for *H. parvifolia* (17.03%), *E. ebano* (13.96%), *A. berlandieri* (14.62%), and *H. pallen*s (15.60%) and in trunk for *E. ebano* (13.72%) and *A. wrightii* (14.41%). The lower amount of extractables was observed with cyclohexane, with minimum and maximum values of 0.67% and 3.36%, respectively.

6.4.6 Runkel Lignin

The lignin content varied significantly ($P < 0.05$) from 28.78 to 35.84% for trunks, 17.14 to 31.39% for branches, and 20.61 to 29.92% for twigs (Table 1.25). The trunks presented higher percentage of lignin in all species, followed by the twigs,

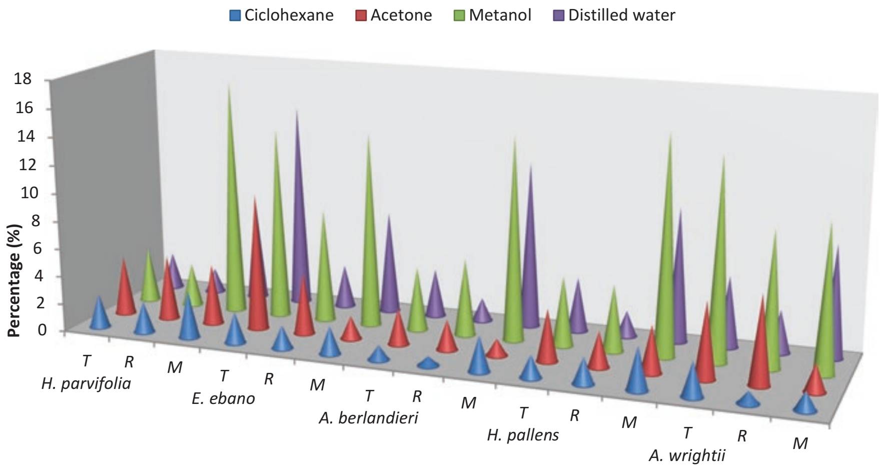


Fig. 1.56 Solubility of different components of five species of the Tamaulipan thorn scrub in solvents of different polarities (*T* trunks, *B* branches, *M* twigs)

except for *H. parvifolia*, where a higher percentage of lignin was reported in branches than in twigs.

6.4.6.1 Holocellulose

The content of holocellulose presented ranges of 24.17–57.22% for trunks, 56.85–67.36% for branches, and 34.86–49.99% for twigs (Table 1.25). The highest values were recorded in the branches, being *E. ebano*, the species with the highest content (67.36%). The trunks presented the lowest values, being also *E. ebano*, the species with the lowest content (24.17%).

6.5 Physical Characteristics

6.5.1 pH

The pH varied from 3.90 to 5.74, reflecting an acid trend for the species studied, in their different growth levels (Fig. 1.57). With exception of *Helietta parvifolia*, the trunks presented very low values compared to other components; that means a tendency to be more acidic in the inside of stem.

However, no significant differences were observed ($P > 0.05$) among species and nor in components.

Fig. 1.57 pH of five shrub and arboreal species of the Tamaulipan thorn scrub in different components

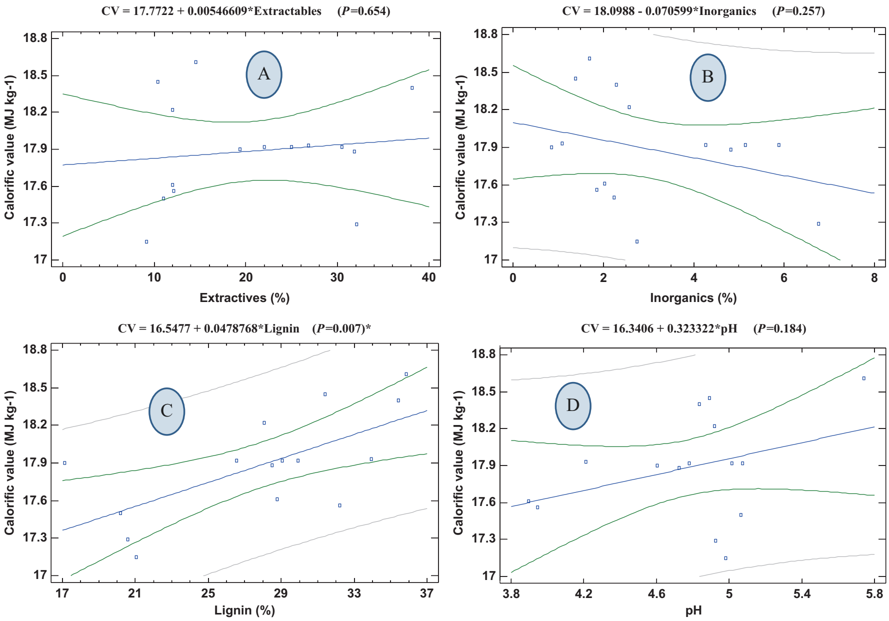


Fig. 1.58 Simple linear regression between calorific value and chemical components (extractive, inorganics, lignin, and pH) of wood

6.6 *Relationship Between Calorific Value and Physical-Chemical Components of Wood*

By correlating the calorific value data with the chemical components, the graphs (Fig. 1.58) and the mathematical adjustment models were obtained along with the coefficients of determination (R^2), as presented in Table 1.26.

Table 1.26 Equations of simple regression and multiple correlations of the combinations between calorific value (CV) and chemical components of wood

N°	Parameter combinations	Equations	R^2	P
1	CV, pH, inorganics	CV = 16.2072 + 0.411899*pH − 0.0951561*inorganics	29.90	0.119
2	CV, pH, extractables	CV = 16.2524 + 0.320308*pH + 0.00501283*extractables	14.47	0.392
3	CV, pH, lignin	**CV = 14.8803 + 0.343794*pH + 0.0488191*lignin**	**58.86**	**0.005******
4	CV, inorganics, extractables	CV = 17.8816–0.123761*Inorganics +0.018522*extractables	22.53	0.216
5	CV, inorganics, lignin	**CV = 16.7467–0.0400171*inorganics + 0.0451078*lignin**	47.03	**0.022***
6	CV, extractables, lignin	**CV = 16.5365 + 0.000864855*extractables + 0.0476448*lignin**	44.08	**0.031***

R^2 = determination coefficient, P = probability at 5%, *significant value ($P \leq 0.05$), **highly significant value ($P \leq 0.01$)

In Fig. 1.58, it can be seen that the calorific value tends to decrease, when the content of the inorganic compounds is higher. This tendency of calorific value is reversed with extractables and with pH, but at low intensity, indicating relatively weak relationship among these variables.

As for lignin, there is a moderately strong relationship with the calorific value, which can be justified in 44% of the cases (R^2). The model obtained can be used for future observations, since it is statistically significant ($P < 0.05$).

Significant differences were observed ($P < 0.05$) among calorific value, extractables, and lignin; but with $R^2 = 44.08$ (Table 1.26), similar to that indicated between calorific value and lignin, there is no difference when adding the extractables in the model.

However, by adding inorganic compounds instead of extractables, the model was slightly improved, with $R^2 = 47\%$ ($P = 0.02$), although the inorganic compounds presented a negative effect on calorific value. When considering pH and lignin, the highest value of R^2 (58.86) was obtained. Therefore, acidity and lignin at the same time have a significant influence on calorific value ($P = 0.005$).

6.7 *Degree of Pollution of Biofuels*

Significant differences were detected among types of samples ($P < 0.05$) and highly significant differences among the different components ($P < 0.01$). In all cases, the sulfates presented very high concentrations than of chlorides. Decreasing values were registered from leaves to the more lignified structures. For sulfates, the concentrations presented the following pattern of ranges: leaves (38.39–57.69 mg L^{-1}) > twigs (12.29–46.18 mg L^{-1}) > branches (1.30–4.49 mg L^{-1}) > trunks (1.05–5.45 mg L^{-1}), as for chlorides, and leaves (1.33–24.13 mg L^{-1}) > twigs (0.89–6.63 mg L^{-1}) > branches (0.46–2.92 mg L^{-1}) > trunks (0.21–2.47 mg L^{-1}), as can be observed in Fig. 1.59. These results highlight that the sulfate ion is abundant in forest biomass.

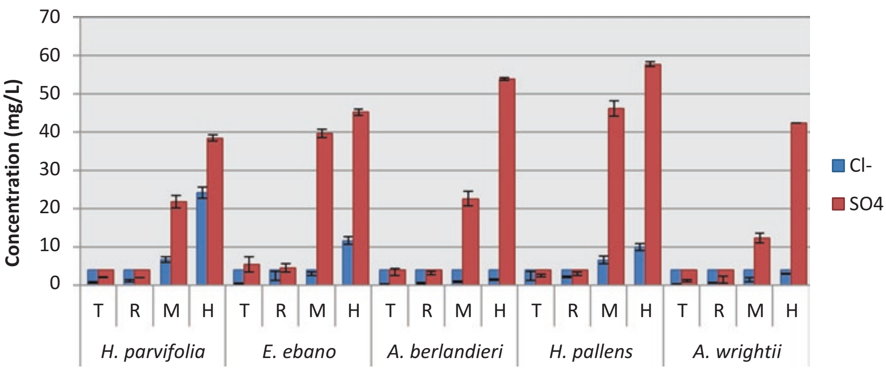


Fig. 1.59 Chloride and sulfate concentrations in different components of five species of the Tamaulipan thorn scrub (*T* trunks, *R* branches, *M* twigs, *H* leaves)

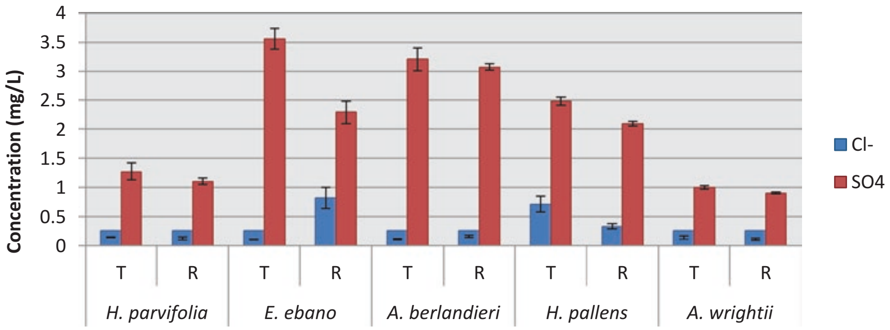


Fig. 1.60 Concentrations of chlorides and sulfates in the charcoal of trunks and branches of five species of the Tamaulipan thorn scrub (*T* trunks, *R* branches)

As for charcoal, there were variations in branches (0.90–3.07 mg L^{-1}) > trunks (0.99–3.56 mg L^{-1}) for sulfates and branches (0.10–0.82 mg L^{-1}) > trunks (0.11–0.71 mg L^{-1}) for chloride (Fig. 1.60).

These ranges are inferior to those observed in the same structures $_{\text{(branches and trunks)}}$ for the samples of wood.

7 Discussion

The present study concentrated on morphology, phenology, biomass, and bioenergy of five timber-yielding plants which may serve as a model to study these aspects of the timber-yielding plants in other regions of the world. It is necessary to mention that sufficient research inputs have been directed on various aspects of more than 30 species of woody plants of the Tamaulipan thorn scrubs as mentioned below. Woody plant species are dominant vegetation in a forest ecosystem and grow together in harmony with its neighbors, showing different mechanisms of coexistence and adaptation in forest ecosystems (Maiti et al. 2014).

7.1 Phenological Development of the Species Studied

7.1.1 Foliation

According to Sayed (1998), the loss of leaves has been observed frequently as a response to drought, aiming at decreasing transpiration, mainly in July and August (summer) where the highest temperatures occur, in addition to a notable drought. In this way, the species under study responded by not producing new leaves as the conditions are extreme. This is in agreement with what was reported by Pavón and Briones (2001) for nine perennial species (three cacti), including *Prosopis* *laevigata*, in a semiarid ecosystem in Mexico (Zapotitlán Valley, Puebla). The loss of leaves as such occurs until winter, in accordance with Reíd et al. (1990), who mentioned that in the scrubs of Northeastern Mexico, winter climatic conditions were significant causes of foliage loss in 1989 when temperatures of −9 °C were reached, in 58 species of scrubland a semi-deciduous behavior in the winter. Similarly, the same authors also do not emphasize the effect of drought and high summer temperatures on leaf loss.

7.1.2 Flowering

For flowering, Cantú-Ayala (1990) reported for *Prosopis laevigata* the period of flowering and fructification in the beginning of March to middle of June during 1965–1986 in Linares, N.L., as well as Alvarado-Vázquez (2003) in the years 2000–2001. According to their observations on *H. pallens* and *Z. fagara*, Alvarado-Vázquez (2003) suggested that those species that have been evolutionarily chosen to develop their flower buds with anticipation possibly have adjusted the anthesis of the same ones with certain environmental conditions (e.g., temperature, precipitation, or photoperiod), with which they risk of bringing the buds to maturity when a certain environmental condition occurs and if this condition is not sustained, the flowers may not complete their development, so the plant before this situation opts to abort them early and not invest resources in flowers that will hardly reach the ultimate objective of producing seeds; and to compensate for these losses of reproductive structures, the plant has developed strategies such as (a) forming a large number of buttons and, in a certain favorable environmental condition, maturing only a part of them, (b) the ability to develop newly and quickly, new reproducers of structures, and (c) small flowers to be able to produce many, and in case of loss, the cost is minimal.

7.1.3 Fruiting

This phenological event was the one that consumed the most time in all the studied species, since from the formation of embryonic fruits until the end of the dispersion, 6 months or more passed. Therefore, it was presented only once in the year of study. But in other species such as *Leucophyllum frutescens* and *Cordia boissieri*, Alvarado-Vázquez (2003) found multiple reproductive events in the year, attributing it to the speed to ripen and disperse fruits and seeds.

With respect to the season of this dispersion of fruits and seeds, the present results indicate that these are more abundant in summer and early winter, which is the consequence of higher flowering peaks in spring and autumn. Summer and winter in theory do not present optimum conditions for seed germination; however, according to Jurado et al. (2001) in the scrubs of Northeastern Mexico, there is no association between the seed production season and the germination season, and on the other hand, Jurado et al. (1998, 2000) and Flores and Jurado (1998) report that the woody plants of the northeastern scrub of Mexico show a tendency of germination in the conditions of late summer and many other species do not show a season of preference for germination. These results support the theory that in the scrub plants, there are other factors, more important than the optimal season of seed germination, that determine the season of seed production, and these may be the availability of resources or pollinating agents and/or dispersers (Jurado et al. 2001).

According to Sharp and Davis (1989), the phenological rhythms of plants are determined by environmental factors such as water, light, and temperature. However, in arid zone plants, water availability may be the main factor (Sayed 1998; Pavón and Briones 2001). This is congruent with the phenological events of the species under study, particularly flowering and vegetative development. However, Alvarado-Vázquez (2003) observed in the species *A. farnesiana*, *A. rigidula*, and *P. laevigata* that the phenological events of flowering and vegetative development are determined at least partially, in addition to water, by other environmental factors, possibly temperature and photoperiod.

It is notable that in the area of the study, the presence of bimodal precipitation pattern, with rains in spring and autumn, separated in midsummer by notable period of drought and high temperatures and in winter by another period of drought and low temperature, determined significantly the phenological events of the species under study, since most of these events occurred in spring and autumn, in addition to the end of winter, before the rains. This is consistent with reports of seasonal systems of vegetative and reproductive development (Murali and Sukumar 1994; Smith-Ramirez and Armesto 1994; Ghazanfar 1997; Ramírez 2002). However, according to Sakai et al. (1999), the synchronized flowering of different species can also facilitate pollination, since it increases the density of floral resources and the attraction of pollinizers.

In this aspect, Gonzalez-Rodriguez et al. (2015) reported the large variations in reproductive phenology (flowering, fruiting, and seed dispersal) of 18 species of the Tamaulipan thorn scrub, Linares. It was observed that different species flower and start fruiting at different periods to maintain harmony in life cycle for coexistence in the ecosystem. The different phases of phenology are also influenced by environmental conditions. Generally germination and reemergence of seedling coincide with the period of rainfall.

Finally according to Maiti and González (2015), the variations observed in the phenology of the woody species studied are dependent on temperature.

7.2 Forest Production

7.2.1 Number of Shoots

In all cases, the number of shoots appears as a useful parameter in the management of these resources, since it has a significant influence on vegetative regeneration and growth. In this way, *A. berlandieri* and *H. parvifolia* would have a high regenerative potential, due to their better resprouting abilities. On the contrary, *H. pallens*, *E. ebano*, and *A. wrightii* would have difficulties in regenerating, because usually they present only one stem or with maximum two shoots of low vigor.

The low number of shoots presented by *Ebenopsis ebano* and *Acacia wrightii* leads to greater spacing between trees in the studied communities, which results in less competition, thus favoring the uptake of light and absorption of nutrients necessary for the formation of new shoots. Estévez (2004) relates the smallest number of shoots in the "Barrosa" to damages suffered in the lignotuber, which are manifested with an absence of shoots.

7.2.2 Total Height

In general, the average of heights was 4.27 m, a value that approximates the average height of 4 m found for the shrub stratum by Jurado and Reid (1989) when describing the composition and structure of a portion of the Tamaulipan thorn scrub in the Northeast of Mexico. In a similar study, Ruiz (2005) established that the average height of the scrub species was 3.28 m, presenting *H. pallens* as the highest height species with 5 m. In another study, García (1999) obtained an average height of 3.2 m, being also *H. pallens* the species with higher height of 5.8 m; this is because the study was carried out in places close to the eastern mountain "Sierra Madre Oriental" that makes this species more prevalent and consequently present higher height.

But because of the frosts that occurred during the winter periods of 1987–1988 (Foroughbakhch and Heiseke 1990), the development of plantations in both height and diameter was affected, so that the results of the plantations do not reflect what was expected in comparison with native scrub, where species are more vigorous.

7.2.3 Basal Diameter (BD) and Diameter at Breast Height (DBH)

The diameter of the trees is presented as a very important parameter to take into account in the forest exploitation, since it indicates the potential use that can be given to the resource. For example, larger diameter species such as *E. ebano* and *A. wrightii* can be used for sawnwood production, while other species may serve other purposes such as firewood, poles, sleeves, etc.

In this perspective, Foroughbakhch and Heiseke (1990) evaluated the increase in diameter of four species through counting of annual rings at breast height, in two communities of scrub in the region of Linares: "scrub of plain" and "scrub of the hill" indicated that, to reach a diameter DBH of 6.5 cm, a tree should take 16 years in the plain and 32 years in the hill. At the age of 32 that actually have the studied plantations, the *E. ebano* and *A. wrightii* diameters exceed 6.5 cm, confirming the predictions made for the two communities (scrub of plain and scrub of the hill).

On the other hand, it was found in the present study that the species with the greatest number of shoots have the smallest diameters. These results are consistent with those reported by Estévez (2004), who relates the decrease of the number of shoots with the increase of the diameter). This can be noted in *Acacia berlandieri*, which recorded the highest number of shoots (7 shoot/tree), but with the smallest diameter (2.77 cm BD and 1.97 cm DBH).

7.3 Volume of Wood

According to Martínez et al. (2006), the purpose of the establishment of forest plantations worldwide is to meet the demand for industrial raw material, domestic use, forage production, construction poles, and/or firewood. The results observed in *Ebenopsis ebano* and *Acacia wrightii* contradict this opinion, since the volume that registered the native scrub was much superior to the one found in plantations. One can see in this the difficulty they have in adapting to artificial conditions (planting), compared to their vigorous and productive development under natural conditions.

7.3.1 Forage Production

7.3.2 Canopy Coverage of Native Species of the Tamaulipan Thorn Scrub

The species *H. parvifolia*, *A. berlandieri*, and *H. pallens* produced more shoots under experimental condition than in native area (Maginot et al. 2014), which may justify the higher surface occupied by its individuals in plantations, as a result of a great competition among them, where each invests in expanding its branches so as to occupy the largest possible surface. On the other hand, *E. ebano* and *A. wrightii* occupied higher surface in its native area, where they presented lower number of individuals per hectare, but with greater spacing. In all the cases, shrub species with greater forage cover presented a denser crown than others with low coverage of their crown projection downward. Consequently, shrubs with denser bearing are closed, and those with a non-dense bearing (smaller area of occupation) are open. According to Wilson and Tupper (1982), the results obtained allow considering the vegetation coverage parameter as an indicator of the impact of grazing or some breeding practice, since any change in it is the first symptom of changes in environmental processes such as erosion, amount of mulch on the soil, and botanical composition.

Branching pattern of woody species in a forest ecosystem acts as a solar panel in the absorption of solar energy during the process of photosynthesis. There are large variations in branching pattern and branching density (Maiti et al. 2015). Woody species possess two types of leaves, open canopy (all leaves exposed to solar radiation compared to close canopy) and close canopy (all leaves not exposed to sun). It is hypothesized that trees with open canopy have higher photosynthetic capacity compared to those with close canopies (Maiti et al. 2015) which is confirmed in this study.

7.3.3 Foliar Biomass

Most scrub species flower and produce leaves at the beginning of spring, as also indicated by the works of Návar and Jurado (2009), which explains the maximum productivity registered in summer and the lowest in winter. These low values recorded in winter show the role of climate as a determining factor in leaf productivity. Summer seems to be the right season for a good leaf development, whereas in winter, different species only need a minimum of leaves for their physiological functions.

In many studies conducted in native scrub, a value of leaf biomass, greater than that found in the present study in experimental plantations, has been evaluated. For example, Yerena-Yamallel et al. (2011) obtained the value of 25 Mg ha^{-1} of leaf biomass in a primary scrub, while Návar (2008) and Burquez et al. (2010), respectively, found 12.93 and 13.03 Mg ha^{-1} for the Tamaulipan thorn scrub. But in a desert scrub, Burquez and Martinez-Yrizar (2011) indicate a value of 6.67 and 10.57 Mg ha^{-1} for thorn scrub. Such variations are due to the different forms of life presented by the different species in question.

On the other hand, Eckstein and Karlsson (1997) verified that there are certain traits of plants that are associated with a high productivity, and the most decisive is the relationship between the leaf surface and its mass. This reasoning was not confirmed in the case of *H. parvifolia*, where it is observed a greater leaf surface, in comparison with the other species studied.

There is a large variability of leaf traits and biodiversity, which help in the coexistence of the species in forest ecosystems (Maiti et al. 2014; Gonzalez-Rodriguez et al. 2016). According to Maiti et al. (2016) who have realized a similar study, the woody species show large variation in leaf surface anatomy and petiole anatomy, which can be related to taxonomic delimitation and adaptation of the species. There is a large variability in venation pattern among species (Maiti et al. 2015) which may be related to conduction capacity and mechanical strength of the species.

7.3.4 Production of Litterfall

The lowest leaf litter production rate was recorded in autumn, with a mean value of 103.59 kg ha^{-1} for all species, indicating that during the autumnal season, the plant reduces its need for food at maximum, preparing to pass the coldest period of the year, so that it is detached from everything that does not need. This is observed more in regions with arid or semiarid climates, where gradual leaf abscission seems to be an adaptation to water stress, as indicated by López-Hernández et al. (2013).

The greatest contribution of leaf litter occurred in the spring, with values of 273.73–296.45 kg ha^{-1}, respectively, for *A. berlandieri* and *A. wrightii*. In a similar study, González et al. (2008) found that the greatest accumulation of leaves occurs within the months of March to May.

Piatek and Alen (2000) mention that the leaves present a high demand of nutrients with respect to the rest of the organs of the tree, with the precision that between

30 and 70% of the total nutrients stored annually are in the leaves. In this way, the amount of leaf litter that returns to the soil and the concentration of nutrients accumulated in it determines the amount of each of the mineral elements that will return to the soil.

In agreement with Kimmins (1997), leaf litter production is generally higher in humid and warm areas with fertile soils, while it decreases in dry and cold areas and with low availability of nutrients. This is because precipitations wash the nutrients of green leaves (Wood et al. 2005). In contrast, drought can increase nutrient concentrations of litterfall. However, the lack of water in the soil reduces the microbial activity that according to Imbert et al. (2004) is responsible for the release of nitrogen, phosphorus, and sulfur. The consequence of this is a slowdown in the decomposition of organic matter, which causes a low productivity in nutrients. In this way, it can be understood that the accumulation of litter is not synonymous with availability of nutrients. Specific studies on the release mechanisms of mineral elements would be needed.

The present study provides values that are within the range defined for plantations established with characteristic species of poor and degraded soils (Lim 1988; Bernhard-Reversat 1993). The monthly variation in litterfall production and its components has been reported previously by Prause et al. (2003) who reported monthly variations ranging from 0.42 to 28.2 g m^{-2} $year^{-1}$. It is also important to remember that the shrub and tree species mainly lignify in the stems and not so much in the leaves as the vast majority of grasses are used for grazing. Hence, there is a greater stability in the nutritional quality of the foliage of woody species over time.

7.3.5 Herbaceous Production

A. berlandieri presented the smallest area of the crown and was the shrub under which the herbaceous presented more development. This can be explained by its composite leaves and their small leaflets (Texas A&M System 2013), which allowed a good uptake of sunlight by the associated species and low altitude for a successful photosynthetic activity. On the contrary, *E. ebano* that presented the greatest coverage showed very little production of herbaceous biomass. Tracy (2014) found similar results regarding the coverage of *E. ebano*, concluding that it presents a dense canopy. In addition, the same author mentions that it is a species of slow growth, with multiple branches that extend in zigzag, and that it needs a large landscape space to mature. These zigzag branches are the source of the impoverishment of the herbaceous stratum observed in the *E. ebano* plots and, consequently, of their low dry matter production.

Given the above, it is possible to emphasize that the forage supply of the native species of the Tamaulipan thorn scrub is very variable, depending on the density of the shrubs. It is maximum in the shrubs more open and minimum in those with high density. That is, plant coverage could be an appropriate indicator of forage production. But with the restrictions observed in *H. pallens*, we can understand Cantú's (1990) approach, who points out that the wide coverage of a species does not necessarily mean that the species is more productive than the one with less coverage.

As for *H. parvifolia*, which produced less biomass in experimental plantation than in its native area, it could be explained by a larger area of occupation in this condition. However, considering the effects of the coverage demonstrated here, this low production of herbaceous biomass is more understandable, considering the study on the biological properties of *H. parvifolia*, carried out by Rovalo et al. (1983), who reported that this species exerts a dominance in number and biomass in its community due to the release of coumarins, alkaloids of the type furanquinolines, and essential oils to the soil, which avoid the germination of other seeds present there. This means that *H. parvifolia* produces an allelopathic effect on the herbaceous plants within their plots.

About the dynamics of availability of DM in question, the grass (zacate) was presented as one of the most important forage species in the region. For Saldivar (1998), several factors give evidence of this, in which the following are highlighted: the area occupied by this species, approximately 1,063,000 ha, dedicated to livestock exploitation; more than 35% correspond to irrigated and temporary grasslands zacate. Likewise, the grasses have a good adaptation to the different ecosystems found in the northeastern region of Mexico, as well as good forage attributes such as protein content (7.5% crude protein on dry basis) and a high level of consumption per part of the animals (3 kg/day of green grass). These and other attributes determine that this grass is highly preferred by many livestock producers not only of the state but also of the northeast of the country.

The determination of the herbaceous stratum is a tool for the characterization of woody species, in accordance with the studies undertaken by Gonzalez-Rodriguez et al. (2016).

7.4 Energy Characteristics and Chemical Composition

7.4.1 Production of Charcoal

The range of 20–30% of charcoal obtained in this study coincides with the results reported by Hernández and Tello (2014) who obtained 22.2–40.3% (average = 30.3%) for the same species. According to Corradi et al. (2013), the yield of commercial charcoal does not exceed 30%, not only for the fact that the raw material influences the yield of charcoal but also due to the conversion process used. In this study, the conditions for obtaining charcoal were controlled.

In Mexico, generally the wood of Encino tree and mesquite is used for charcoal production. It would be advisable to experiment with other species of semiarid zones that could offer an alternative income to the population that inhabits those regions of Mexican Republic. The results obtained in the present study allow positioning the five species studied within the species to be considered in this process using both trunks and branches. However, it is necessary to implement management plans that allow the use of these species for charcoal production (Galaz 2004).

The yields of carbonization were varied due to different factors, among which are equipment and processes used, basic density, chemical composition of wood, degree of depletion, extractive content, and moisture content (Romahn de la 1992). As for the equipments, an important factor is the kind of oven; the pit type used generates charcoal with greater weight, as a result of using low temperatures (<600 °C), in comparison with the Brazilian beehive where the temperatures reach near to 1000 °C (Bustamante et al. 2013). The factors that influence the pyrolysis are the carbonization radius or accumulation of heat, characteristics of atmosphere, pressure, catalysts, characteristics of the biomass (chemical composition, content and composition of the ashes, sizes and form of the particles, density, moisture content, etc.), temperature of the process, and thermal pretreatments (Guardado et al. 2010).

7.4.2 Quality of Biofuels

7.4.2.1 Moisture Content

The registered moisture content for charcoal is well below 8%, which represents the standardized value in accordance with international standards, according to Carrillo-Parra et al. (2013), who defined charcoal as a material with a low moisture content and low hygroscopicity. For them, the humidity values greater than 8% induce the consumption of more materials during combustion, for evaporation of excess of water. Under these conditions, it is known that the product is more resistant to biodegradation and alterable with difficulty in normal atmospheric conditions and not affected by biological agents which degrade the wood. For wood samples, a part of the twigs of *A. berlandieri* and branches and twigs of *A. wrightii* which presented lower values of 8% (7.42%, 7.97%, and 6.88%, respectively) and the other values were much higher than 8%. The higher value of moisture content (12.22%) was registered in the trunk of *E. ebano*.

The water requires 2300 kcal/kg for vaporizing and 1500 kcal/kg for reaching to 700 °C during pyrolysis and gasification. Excessive moisture content prevents adequate temperatures in the carbonization furnace, as well as problems in the regulation and control of the process. On the other hand, more unburning and slags occur, and fume is generated with high CO content. Also, jams and shutdowns occur in systems, in supply of combustion equipment, and in the silos, valve, etc. (Ortiz-Torres 2006). The moisture content is then presented as the key factor, very important for its influence on the quality of a biofuel.

7.4.2.2 Volatile Materials

The values obtained in this study are lower than the range of 20–30% established by Williamson (2006). The volatiles in charcoal were found with very low quantity compared with the samples of wood, which proceed to its release during the carbonization process. It tends to be more environmentally friendly, using charcoal as biofuel, than wood and/or its by-products.

The trunks of *E. ebano*, *H. pallens*, and *A. berlandieri* showed a lower volatile content than their branches, presenting an advantage from the energetic point of view, because they burn slower than the branches, which have higher quantity of volatiles, as indicated by Cuvilas et al. (2014) that the species with low quantity of volatile materials burn very slow than those with higher quantity.

On the other side, the result of this low content of volatile materials is a clean, environmentally friendly combustion and key for efficient use of the resource, important characteristics required for thermoelectric center, as advocated by Luxán and Jiménez (2003).

7.4.2.3 Ash Content

The high values recorded on the leaves of all species, followed by the twigs, support the idea of trunk demineralization toward leaves. This is because before the leaves fall, the sap is concentrated in them and when detached demineralizes the trunk (Guadalfajara-Alcalde 2015).

Determining the chemical composition of *Haematoxylum brasiletto*, Ávila-Calderón and Rutiaga-Quiñones (2014) found values of 4.31% in sapwood and 2.88% in heartwood, values similar to the averages obtained in this work, for branches and trunks, respectively. According to Cuvilas et al. (2014), low ash fuel is desirable, since its accumulation messes up the heat exchangers and obstruct the flow of flue gases, with the risk of causing problems in the reactors (Werkelin et al. 2011). Respond to this expectation, the species *A. wrightii*, with the lowest ash contents obtained in its trunks and branches, with values of 2.05 and 1.68%, respectively. But these values differ slightly from those presented by Hernández and Tello (2014), who found that the ash content did not exceed 2%; their values were 0.47, 0.96, 1.31, and 1.34 for *A. wrightii*, *H. parvifolia*, *E. ebano*, and *H. pallens*, respectively.

Obernberger and Thek (2010) established that with high ash contents, constant cleaning of combustion equipment is required. In fact, high values of inorganic elements can cause the particles to disperse and stick in the interior of heat exchangers and power plants; in the long term, it can obstruct the flue gas channel and induce corrosion of furnaces, reactors, turbines, and emission control devices (Liu and Bi 2011; Werkelin et al. 2011). The size of the biomass significantly influences the ash content. Thus, Somoza et al. (2014) found significant differences between the ash contents of wood chips of four forest species *Pinus* sp., *Betula* sp., *Quercus* sp., and *Populus* sp., sieved with 16 and 8 mm meshes, for splinter production and pellets with fine fraction, being more favorable for the first size of mesh to include lower percentage of finer fractions.

Several authors have noted higher ash contents in the fine fractions of residual forest biomass that form the thinner leaves, twigs, and trunks (Nuñez Regueira 1996, 1997; Núñez-Regueira et al. 1999, 2004; Kauter et al. 2003, Pérez et al. 2008, García et al. 2012), owing to greater relation of bark/wood (Werkelin et al. 2005, 2011;

Vega-Nieva et al. 2010). For example, Vega-Nieva et al. (2014a) observed that the average values of the forest residuals with bark and leaves of various species of Northeast Spain only would be suitable for production A2 or B on the basis of its ash contents. According to Merino et al. (2005), forest residues with leaves present no admissible ash values, in addition to a high risk of formation of slag or sintered, due to its high content of nutrients.

In addition, different degrees of pollution by soil are another factor that can increase the ash content of residual forest biomass (Vega-Nieva et al. 2014b). Lastly, the cutoff date and the time that they remain in forest are factors that affect the ash content of the forest residues (Kauter et al. 2003; Werkelin et al. 2005, 2011; Nuñez Regueira 1996, 1997; Núñez-Regueira et al. 1999, 2004). A prolonged residence time in the forest can reduce nutrient and ash content in the residues by depositing the finer fractions in the soil; by improving the quality of the residues as biofuel and minimizing the nutrients extracted (Ortiz 2006; Merino et al. 2005), which should be pondered by the risk of fire; and by keeping the residues in the forest without crushing (Stephens and Moghaddas 2005).

It should be noted that fuels with moderate or medium ash content may present a high risk of corrosion or formation of slags that limit the operation of the boiler by presenting nutrients that form sintered or corrode the exchangers. This is why, in addition to the ash content, the composition of these ashes and their associated risk of sintering or slagging should be studied (Vega-Nieva et al. 2010, 2014a, 2016), as discussed in the section below.

7.4.2.4 Fixed Carbon

The species *H. parvifolia*, *E. ebano*, and *A. wrightii* and the trunk of *H. pallens* presented fixed carbon content more than 75%, as required by the European market for the use of charcoal for industrial purposes (Carrillo-Parra et al. 2013). But there are some industries that buy charcoal regardless of whether the fixed carbon content reaches any amount.

On the other hand, Demirbas (2003) indicates that low fixed carbon content increases friability and fragility and decreases the resistance to compression and cohesion.

7.4.2.5 Calorific Value

For charcoal, the values obtained in the present study are similar to those reported by Masera et al. (2005), ranging between 29,000 and 35,000 KJ kg^{-1}, presenting as an important source of energy.

As for the leaves, the high values registered of calorific value can be attributed to the presence of extractable substances, since according to Kollmann (1959), their increase seems to increase the calorific value. These values of calorific value for the wood samples of the present study are similar to those found by Quirino (2005) in eucalyptus and are within the range of 17,882–19,629 J g^{-1} reported by Francescato et al. (2008) for conifers, which is an interesting result, which makes possible the use of residues of these five species of the Tamaulipan thorn scrub studied for energy purposes, since conifers have always been considered to have a higher heat output than hardwoods (Guadalfajara-Alcalde 2015).

From the energy point of view, Girard (2002) found that there is no difference among charcoals of the different species, although it may have different physical properties. In this way, the production and use of charcoal can be extended to what is produced by branches, in order to reduce the pressure on this resource, which is usually done using the trunk, which is the dense part of the tree. This alternative gives greater utility to species that produce many shoots, with small diameters, reducing the pressure exerted on stem species with larger diameters.

7.4.2.6 Relationship Among the Characteristics of the Tested Biofuels

Charcoal obtained as the main constituent is mainly constituted of fixed carbon, whereas wood is constituted mainly by the volatile materials. Guardado et al. (2010) found similar results, indicating that a greater amount of volatile gases corresponds to a lower amount of fixed carbon and vice versa.

With the highest values of ash contents in charcoal than in wood samples for both trunks and branches, it can be understood that for more fixed carbon contained in a biofuel, greater ash content will be produced.

These variations are at the basis of the difference in the quality of each type of material as biofuel, implying that most biomass energy is contained in organic matter. However, Jenkins et al. (2011) established that the inorganic fraction is also important for the design and operation of the combustion system, particularly with regard to ash encrustation. Its high-volume generation represents a challenge for the chemical industry and energy production, due to costs and logistics for its collection, transportation, handling, and storage (Kargbo et al. 2009).

Jenkins et al. (2011) also related the ash content to the calorific value, concluding that species with less than 1% of ash usable have a calorific value of about 20 MJ kg^{-1}, while each increase of 1% in the ash results in a decrease of 0.2 MJ kg^{-1}, because the ash in general does not contribute substantially to the heat released by the combustion, although some elements in the ash can catalyze the thermal decomposition, so that the ash decreases the available energy per unit mass (Jenkins et al. 1998). This result also explains the close relationship among fixed carbon and calorific value ($P < 0.01$), which again corroborates the one found in the correlations among the carbon content and the calorific value by Jenkins et al. (2011), who established that each increase of 1% in carbon raises the calorific value approximately to 0.39 MJ kg^{-1}.

In addition, ash has an alkaline reaction when mixed with water, the pH of the solution increases and induces corrosion of the metal (Karltun et al. 2008). For this, Obernberger et al. (2006) indicate that the determination of ash concentration and composition is essential for the choice of appropriate combustion and gas cleaning technologies.

The moisture content does not present a significant relationship ($P > 0.05$) with other variables, so that it does not influence the other properties of charcoal. However, Carrillo-Parra et al. (2013) obtained a relation among moisture content and calorific value. As for the volatile material content, a significant relationship ($P < 0.05$) with ash was detected.

7.4.3 Inorganic Substances Obtained from the Microanalysis of Ash

According to the results obtained, the elements calcium, potassium, and magnesium are presented as the main components of the inorganic substances in the wood. This corroborates the results of Fengel and Wegener (1989) and Rojas (2013), who have also found a greater proportion of these elements in the wood ash of four conifers (*Abies religiosa*, *Pinus montezumae*, *P. pseudostrobus*, and *P. leiophylla*), with values up to 80%. These elements exist in the wood as oxalates, carbonates, and sulfates (Hon and Shiraichi 2001) and belong to the group of seven known as macroelements or macronutrients (magnesium, phosphorus, sulfur, potassium, calcium, and nitrogen) that plants require for their full growth (Gil 1995).

According to Martínez-Pérez et al. (2012), calcium is the major interchangeable cation of fertile soils, which is associated with soil organic matter and which in the plant cell is important in the formation and maintenance of cell membranes and lipid structures by its facility to establish reversible links. The high content of this element is caused by the presence of calcium oxalate crystals found mainly in axial and radial parenchyma cells (Chattaway 1956; Carlquist 2001).

As it concern, potassium forms associations with proteins and helps to activate enzymes (Gil 1995). A high content of K_2O (15%) in wood ash attacks household ceramic materials when the combustion temperature is high (Guadalfajara-Alcalde 2015). But with the low temperatures that are handled in practice, this situation does not occur.

For magnesium, its most important function is related to photosynthesis and glucose metabolism (Gil 1995).

On the other hand, traces of N (0.17–1.53%), P (0.06–5.51%), Na (0.02–1.3%), and Si (0.004–7.59%) were found in all the structures. Silicon is an element that gives rigidity to the leaves, thus improving photosynthesis (Gil 1995). The range recorded by this element is very wide, compared to that found by Martínez-Pérez et al. (2012), from 0.04 to 1.20% in the bark of six fruit trees.

For sodium, the upper limit of the range obtained is similar to the averages reported by Correa-Méndez et al. (2014) in sawdust and chip ash, 1.4% and 1.0%, respectively. These values approximate the lower limit of the range 2.0–4.4% found by Revilla (2011), when analyzing wood of *P. cembroides*, *P. johannis*, *P. maximartinezii*, and *P. pinceana*. For the content of P, Correa-Méndez et al. (2014) published average values of 4.9% in sawdust ash and 4.0% in chip, which is within the range obtained in the present work.

It is estimated that the composition of the ash determines its melting point, i.e., the temperature at which it forms slag. The lowest melting temperatures are generally those of charcoal, with high silica content. Charcoal ash contains sodium and potassium carbonates and large amounts of silicate combined with a wide range of metals. According to Thyrel et al. (2013), these materials are prone to the formation of slag and fouling at high temperatures, which can reduce the efficiency of the combustion system.

Woody species show variations in leaf macro- and micronutrients, which may be related to the productivity of species (Gonzalez-Rodriguez et al. 2015), nutrient profile, as well as in biodiversity of leaf chemistry (Maiti et al. 2016).

7.4.4 Chemical Elements (C, H, N) in Wood and Charcoal

According to Raju et al. (2014), the biomass fuel quality is affected by the proportion of these elements. For Bustamante-García et al. (2015), hydrogen is found in biomass in the form of moisture and water of hydration or as a constituent of the silicates of the mineral matter. Therefore, it allows determining the amount of water that will be produced during the combustion.

The hydrogen and oxygen molecules released in the form of vapor provide a series of reactions resulting from the reorganization of the compounds to form synthesis gas, mainly H_2, CO, and CO_2. The synthesis gas is converted into methanol ammonia or other products (Demirbas 2003). Oxygen is considered an indicator of the oxidation range of the biomass. Calventus et al. (2009) assert that the amount of oxygen decreases the calorific value of the fuel. In addition, the amount of oxygen is related to the formation of nitrogen oxides emitted in the fuel gases. With the same technologies, the wood species influences the charcoal obtained in a simple way; plant species with higher carbon content produce coals with more fixed carbon and higher calorific value (Marcos 1989).

Nitrogen is related to the formation of nitrogen oxides. The amount of nitrogen in the biomass does not have negative effects on the environment when compared to fossil fuels (Demirbas 2003; Serrano 2009).

7.4.5 Chemical Components of Wood

7.4.5.1 Extractable Substances

The results show that the extractables yield more in twigs. However, the trunks presented more content than the branches. Rojas (2013) reported a similar result in conifers, concluding that the heartwood contains, in general, a greater percentage of extractable components than the sapwood.

The pattern obtained by successive extraction, of lower solubility in nonpolar solvents, followed by higher solubility with solvents of medium polarity and decreasing again in the aqueous extraction was also observed in the heartwood of *Andira inermis* (Téllez et al. 2010) and in the heartwood of *Enterolobium cyclocarpum* (Ramos-Pantaleón et al. 2011).

The lowest amount of extractables obtained with cyclohexane is higher than the range of 1.03–1.33% found by Ávila-Calderón and Rutiaga-Quiñones (2014) in sapwood, heartwood, and bark of *Haematoxylum brasiletto*.

It is known that extractables of heartwood and bark may have high resistance to biodeterioration; in this way, *Haematoxylum brasiletto* bark extract has been found to inhibit bacteria and yeasts. In this extract, hematoxylin, brasilin and gallic acid have been identified as the major inhibitors of these biological agents (Rivero-Cruz 2008).

The higher yields obtained in the methanolic solvent of the species under study suggest that these species would have a strong ability to resist disease. This property can be used for plant health, such as bactericide and fungicide.

On the other hand, the extractable content influences the physical and technological properties, increasing the dimensional stability and mechanical resistance or decreasing the point of saturation of the fiber and the equilibrium moisture content (Poblete et al. 1991; Ávila and Herrera 2012). The yields reached in this work are higher than the range of 2.4–7.7% reported for pine species (Fengel and Wegener 1989; Rodríguez 2005; Fonseca 2006). This indicates that the species of the Tamaulipan thorn scrub are less vulnerable to different changes of humidity, allowing their multi-use in an efficient manner in different sectors such as construction, furniture, handicrafts, and, above all, the bioenergetic sector, for integrated systems.

7.4.5.2 Runkel Lignin

The runkel lignin range obtained for the trunks is superior to those found by Rutiaga et al. (2010) in the heartwood of some tropical species such as *Dalbergia granadillo* (26.25–26.50%) and *Platymiscium lasiocarpum* (25.25–25.95%). The higher percentage of lignin presented by the trunks for all the species, followed by the twigs and then by branches, suggests a variation of lignin content in the different components of a tree, unlike that reported by Fonseca (2006), who determined that there was no significant difference for the lignin contents at three tree height levels in *P. oocarpa* and *P. maximinoi*.

The ranges recorded for both branches and twigs of the species studied include the highest value published by Bernabé-Santiago et al. (2013) for wood of *Pinus leiophylla* (28.5%) and by Rutiaga Quiñones (2001) for heartwood of *P. pseudostrobus* (27.6%).

From the physical point of view, the wood suffers dimensional changes, due to the variations in the moisture content in its interior. Facing to these changes, the lignin content plays an important role in the behavior of the wood (Bárcenas-Pazos and Dávalos-Sotelo 1999). Therefore, the high content of lignin registered in these species of arid zones makes them as low contraction species, compared to the relatively high contraction published for the wood of *P. montezumae* (radial 5.0%, tangential 6.6%), *P. oocarpa* (radial 3.3%, tangential 4.4%) (Herrera-Ferreyra and Bocanegra-Ojeda 1996), and *P. michoacana* (radial 3.1%, tangential 6.9%) (Sotomayor-Castellanos et al. 2010).

As for the relationship between lignin and the mechanical properties of wood, El-Osta et al. (1981) found that the high lignin content provides greater hardness in the cell wall which contributes to increase its resistance to compression efforts. In contrast, Bodig and Jayne (1993) explain that the contribution of lignin is not fully tested for the cell wall to resist compression efforts due to the restriction of transverse swelling of the microfibrils. In this way, the higher lignin content of the infected wood does not explain the decrease in PPS in parallel and perpendicular compression, determined in *Pinus pringlei* wood infected with mistletoe (Acevedo and Ambriz 1999). The decrease in the efforts mentioned in the infected wood may be related, as already discussed, to the holocellulose content and the anatomical structure and not to the lignin content.

7.4.5.3 Holocellulose

The holocellulose consists of cellulose and hemicellulose; these are, to a large extent, responsible for the mechanical resistance of the wood. The cellulose is extremely resistant to tension and other efforts in the longitudinal direction, due to the covalent bonds within the pyranose ring and between monomeric units. The tensile resistance of the cellulose molecules is due to the hydrogen bonding, which allows the molecule to absorb the efforts to this solicitation (Bergander and Salmén 2002; Winandy and Rowell 2005). Other recent works have shown that hemicelluloses positively influence the compression resistance, hardness, and in general its resistance in the transverse direction (Winandy and Lebow 2001; Bergander and Salmén 2002; Konnerth et al. 2010). Acevedo and Ambriz (1999) found a low proportion of holocellulose in infected wood than in healthy wood, indicating that this may explain the decrease in the wood effort values of *Pinus pringlei* in static flexion: at the proportionality limit (ELP) in wood infected with mistletoe (586 kg/m^2), relative to healthy wood (766 kg/m^2); in parallel compression, the decrease of ELP (347 kg/m^2) and maximum effort (Emax *R* 386 kg/m^2) in infected wood compared to healthy wood (418 kg/m^2 and 468 kg/m^2, respectively); and in perpendicular compression the decrease of the ELP of infected wood (116 kg/m^2) with respect to that of healthy wood (132 kg/m^2).

7.5 *Physical Characteristics*

7.5.1 pH

The pH presented a tendency to be more acidic in the interior of the stem, which coincides with the results found in broadleaf by McNamara et al. (1970). A similar result has been reported in heartwood and sapwood of *P. montezumae* and *P. pseudostrobus* by Rojas (2013), with values of 4.81 and 4.94, respectively.

The absence of significant differences ($P > 0.05$) among species and plant components can be attributed to a greater amount of acetic acid, acyl compound, and the interaction among them, as has been demonstrated in some broadleaf species (Fengel and Wegener 1989; Volz 1971).

As for the role of pH, it is pointed out that it is a characteristic that influences on the use of wood, causing the corrosion of metals in contact with it, in the fixation of certain chemical preservatives, etc. (Fengel and Wegener 1989; Choon and Roffael 1990). The present study offers a vision to be considered undoubtedly for an efficient use of the wood of the Tamaulipan thorn scrub.

7.6 Relationship of Calorific Value with the Physical-Chemical Components of Wood

The tendency of calorific value to decrease with higher amount of inorganic compounds agrees with literature (Fengel and Wegener 1989; Martínez-Pérez et al. 2012). The model obtained from the moderately strong correlation of lignin with the calorific value coincides with the one reported by Francescato et al. (2008) that the high values of lignin in fuel materials increase the quality as fuel. Guadalfajara-Alcalde (2015) reports a great calorific value in conifers, due to its richness in resins (9000 kcal kg^{-1}) and its higher lignin content (6000 kcal kg^{-1}).

Rojas (2013) reported that lignin is one of the largest industrial wastes in the world, when it is discarded in the form of lignin derivatives in sulfite liquor used in the industrial processing of wood into paper pulp. This residue is frequently proposed as a fuel for the generation of heat by determining the combustion properties of lignin-rich residues.

By adding the extractables in the model, no significant differences were observed, which contrasts with Browning (1975) cited by Cunha et al. (1989), who asserts that the calorific value is higher when there is more content of lignin and extractables, because they contain less oxygen than the polysaccharides present in the holocellulose (cellulose and hemicellulose).

On the other hand, some wood components have a greater or less influence in the development of the carbonization and in the obtainment of products of the same. Thus, for example, the higher content of holocellulose increases the production of distillates and the charcoal yield decreases. On the contrary, the presence of lignin increases the production of charcoal (Bravo García 1995; FAO 1983). The yield of charcoal also shows some variation with respect to the type of wood, since the lignin content in the wood has a positive effect on the charcoal yield. A dense wood also tends to produce a dense and strong charcoal, which is also desirable. However, very dense wood sometimes produces brittle coal, since wood tends to crumble during carbonization (FAO 1983).

Among the main characteristics that define the quality and use of charcoal, we can consider the percentage contents of fixed carbon, volatile material, ash, moisture content, wood-charcoal yield, density, and calorific value (Pérez and Compean 1989; Sánchez Rojas 1996).

7.7 Degree of Contamination of Biofuels

According to Orozco et al. (2005), sulfate together with other ions exerts a fouling power and hence the importance of their determination for industrial uses, especially in the case of boilers, since this phenomenon in such equipment can reduce its effectiveness and, consequently, its lifetime. A wide concentration range of this ion is found in acid rains, and its determination provides valuable information regarding pollution and environmental phenomena; in addition, it can provide data on sulfuric acid from sulfur dioxide present in the atmosphere (Arboleda 2000).

It is known that sodium and magnesium sulfates have a laxative action, so an excess of them is not desirable (Guzmán 2011; Ríos et al. 2001). The sulfate ion precipitates in acid medium with barium chloride forming uniformly sized barium sulfate crystals. The concentration of sulfates in the sample and the luminous absorbance of the suspension can be measured spectrophotometrically at 420 nm, being the SO_4^{2-} concentration determined, with respect to a calibration curve, according to standardized methods for potable and residual water analysis (APHA, AWWA, WEF 2012).

The chloride ion (Cl^-) for its part is one of the major inorganic anions in natural and residual water (Castillo-Flores 2010). The chloride content is variable and is mainly due to the nature of the cross lands. Usually, the chloride ion content of natural waters is less than 50 mg/L.

In potable water, the salty taste produced by Cl^- is variable and depends on the chemical composition of the same. Like chlorides, the sulfate content is very variable and can range from a few milligrams per liter to hundreds of milligrams per liter.

Sulfates can have their origin in waters that pass through land rich in gypsum or pollution with industrial wastewater. The sulfate content does not present a problem of potability to drinking water, but sometimes contents above 300 mg/L can cause gastrointestinal disorders in children. It is known that sodium and magnesium sulfates may have a laxative action, and an excess thereof in water intended for human consumption is undesirable.

8 Conclusions

The study on the development of the five timber species of the Tamaulipan thorn scrub constituted a highly relevant stage, since it is indispensable in the optimal design of management and utilization strategies, to achieve a good production of this productive system, in order to raise projects, whether for livestock use (foliage), forestry, or bioenergy.

The present study on five species will serve as a model to study all these aspects of timber-yielding plants in other regions.

Most of the species studied detached their leaves and gradually renewed them in the favorable seasons of the year. Fruiting in most cases occurred immediately after flowering, and, therefore, the number of events was similar, except for *E. ebano* and *H. pallens* in which floral abortion events occurred. The fruits rapidly passed from the embryonic stage to immature fruits and remained at this stage for 2–3 months until reaching maturity around the month of August. Mature fruits were particularly abundant in the months of July–August and November. These variations in both duration and intensity of vegetative and reproductive development of the Tamaulipan thorn scrub were presented according to climatic conditions, constituting as a feasible tool for the management of this resource, so that potential changes in their dynamics can be predicted, to ensure its permanence and sustainability. The results obtained justify the great potential of phenological studies to understand the influence of climatic factors on plants.

The coverage estimation of shrubs and trees of the Tamaulipan thorn scrub was used to evaluate its forage productive capacity, based on the herbaceous species developed under these species, complemented by the characterization and description of this herbaceous vegetation. This ability contributes to ensuring a nutritious diet for livestock, according to the protective influence of the Tamaulipan thorn scrub and to the development of herbaceous plants. It was observed that there is not necessarily an influence of the scrub canopy on the development of the herbaceous stratum. However, the main Tamaulipan thorn scrub species offered different availabilities of herbaceous biomass. In this dynamics, *Havardia pallens* and *Acacia wrightii* were presented as the species with the best potentialities, favoring the development of *Lantana sp.* and *Stipa lessingiana* (zacate) that have good forage attributes. The management of this supply should be directed toward the control of the shrubs, avoiding that they close in excess, to limit in this way the increase of the risk of fires, the loss of pastable resources, and the herbaceous diversity. This guidance allows for long-term trends for producers. In this sense, it would be advisable to increase the space among the individuals of *Helietta parvifolia* when planting them, since they are very closed species, same with *Ebenopsis ebano* that requires a lot of space to grow in good conditions.

The fall of leaf litter in plantations of *H. parvifolia*, *E. ebano*, *A. berlandieri*, *H. pallens*, and *A. wrightii* is on average four times lower than leaf biomass, with significant variation by seasons. This balance establishes a functional relationship between the production and the loss of leaves, which allows assessing the ability of these species to contribute organic matter and nutrients to the soil for the growth and development of vegetation, under very unfavorable soil conditions. This contribution of organic matter varied according to the species studied, but the average value highlights the importance of these species for their potential utility in the rehabilitation of degraded sites. To achieve this, a combination of trees is recommended, so that the litter has different levels of carbon and nitrogen concentration, for a better quality of the humus formed. The fall of litter becomes, then, a determinant tool in the management of the ecosystems in question, reason why its determination opens the door to the possibility of being valuable in ecological restoration and reforestation programs. The charcoal production proves to be a good option for energy generation, since it was presented in this study as an efficient fuel, because of its considerable carbon content, which induces its high calorific value. The charcoal of the species studied in the present work, both trunk and branches, was suitable for domestic or industrial use, as it complies with established international standards. By selecting these species for use as biofuel, it contributes ineluctably to socioeconomic development, without compromising the existence of the resource while at the same time taking care of the health of the environment for the well-being of the settler.

According to the chemical analysis, the content of inorganic substances, extractables, and cellulose proved to be in compliance with the corresponding standards. However, there were some variations between species and also in the different components of each. The pH has an acid tendency in the different components of all the species. The main constituents of the ashes are potassium, calcium, sodium, silicon, phosphorus, and magnesium; also chlorine is found in significant concentrations in biomass, where calcium is proved to be the largest element of the ashes of these species. These elements are divided according to the ascending sequence trunks <branches < leaves. The extracts showed the sequential pattern methanol > distilled water > acetone > cyclohexane, according to a decreasing performance gradient, with the highest proportion in twigs for *H. parvifolia*, *E. ebano*, and *A. berlandieri* and in trunks for *E. ebano* and *A. wrightii*. As for lignin, the highest values were found in trunks of all species, followed by twigs, except with *H. parvifolia* where the highest percentage of lignin was reported in branches than in twigs. The calorific value presented higher value in *H. parvifolia* trunks, followed by *E. ebano* and *A. wrightii*; this same pattern was observed in branches. The correlation between lignin and pH resulted to be determinant in the energy potential. However, the total content of inorganic substances is a factor to consider, since it indicates the monitoring that is required for energy use.

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Chapter 2
Research Methods of Timber-Yielding Plants (in the Example of Boreal Forests)

Abstract Many methods for the study of timber-yielding plants exist. These methods encompass a variety of issues. They are based on traditional approaches and approaches of nonlinear dynamics. The greatest attention is paid to the study of forest stand biomass. Regression method is considered the most accurate and versatile. The set of functions is available to approximate tree biomass depending on its diameter. Allometric function is the most biologically driven. However, all these biomass functions belong to the regression method. They cannot claim to be a universal dependency, which can be used in a wide age range and geographic range. Therefore, prediction on this basis is not accurate. Logistics systems of equations are more versatile. Our research has shown that the use of systems of differential equations gives good results for the study of the joint growth of two wood species. This approach allows one to predict the role of valuable wood species in the forest stand structure in the process of reforestation. It is useful for the planning of forest management and environmental measures. However, the gap between the mathematical and experimental ecology continues to exist. The development of new universal methods of forecasting the state of timber-yielding plants and their ecosystems is still relevant.

Keywords Timber-yielding plants • Methods for the study • Traditional approaches • Regression method • Allometric function • Joint growth of wood species • Differential equations • Methods of nonlinear dynamics • Forecasting

1 Introduction

Forests occupy ≈52% of the Earth's land surface (Boisvenue and Running 2006). According to FAO, as of 2000, the world has 3.9 billion hectares (ha) of forests with 187 million ha (5%) in forest plantations (Siry et al. 2005). These ecosystems play a large role in the world's carbon budget, and their dynamics, which are likely to be responding to global changes in climate and atmospheric composition, have major economic implications and impacts on global biodiversity. They provide renewable raw materials and energy, maintain biological diversity, mitigate climate change,

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protect land and water resources, provide recreation facilities, improve air quality, and help alleviate poverty. At the same time, forests are affected by fire, air pollution, pests, and invasive species and are the primary targets in many countries of agricultural and urban expansion (Global Forest Resources Assessment 2005). Forest productivity is one of their main characteristics. It defines the flow of processes in the forest ecosystems. This characteristic is used in environmental monitoring and modeling of the impact of global climate change on forest ecosystems and their biodiversity. Forest biomass is increasingly being considered as a source of sustainable energy. It is crucial, however, that this biomass be grown and harvested in a sustainable manner (Stupak et al. 2011; Evans et al. 2013). Timber-yielding plants are the most important for forestry and the economy. Current changes to forest production factors (light, water, temperature, and site nutrient) over the last 55 years have been documented in peer-reviewed literature (Boisvenue and Running 2006). Predicting the state and productivity of timber-yielding plants (and their ecosystems) under different conditions, based on their biology, is the central problem of the sustainable resource management concept (Maiti et al. 2016). The estimated accuracy of productivity of timber-yielding plants will depend on many factors. Although there is a long history of forest net primary productivity studies in the ecological literature, current understanding of ecosystem-level production remains limited. Forest net primary productivity cannot be directly measured. It must be approached by indirect methods. To date, field measurements have been largely restricted to a few aspects of net primary productivity; methods are still lacking for field assessment of others, and past studies have involved confusion about the types of measurements needed (Lu 2006; Somogyi et al. 2007; Clark and Kellner 2012). Further development of approaches and techniques to study the structure and productivity of forests is essential. Boreal forests are convenient objects for this purpose.

2 Estimation of Aboveground Biomass

2.1 Sample Plots

The forest diversity is extremely large. However, we can divide the forest into fairly homogeneous plots, and we can study them. This method allows us to determine the structure and productivity of forests on the basis of its constituent sections. Sample plots should be representative of a particular category of forests.

The second important point is to establish the size of the sample plots. Choosing the size of the sample plot depends on the stand density. The sample plot should include at least 400 trees in young forests, while 200 trees are sufficient for old-growth forests. If the number of trees on the sample plot is smaller, the error in determining the characteristics of it increases. The number of sample plots depends on forest biodiversity. All major forest types should be investigated. Also, sample plots shall cover a maximum age range and density range. All the trees growing on the sample plot should be explored. The diameters and heights should be measured. Vital status should be determined. Selection of plots on such a scheme allows the use of regression analysis. This allows you to identify the features of the structure and productivity of forests in age gradient and edaphic gradient. If the forest is very dense, it is difficult to measure the height of trees. In this case, the method of sample trees should be used.

If it is not possible to measure all the trees on the sample plot, then the method of model trees is used. Two methods exist to select the trees. Trees are selected systematically. For example, every fifth or tenth tree is selected. Selection of representative trees for each studied category is another method. The result depends on the method of selection and the number of sample trees.

2.2 Calculation of the Aboveground Biomass of Forest Stand

Madgwick and Satoo (1975) allocated the three most common methods of the forest stand biomass estimation: the average tree method, trunk cross-sectional area method, and regression method. Regression method is considered the most accurate and versatile. The equations are calculated by the sample trees. The set of functions are available to approximate the tree biomass depending on its diameter. The straight line is used to approximate the most frequent. Polynomial functions and exponential functions are also popular (Madgwick and Satoo 1975). The most common mathematical model in biomass studies takes the form of the power function $M = aD^b$ where a and b are the allometric coefficients to be determined by empirical data, and M the total aboveground tree dry biomass for a specific diameter at breast height, D. Allometric function is the most biologically driven (Hoffmann and Usoltsev 2002; Teobaldelli et al. 2009; Mugasha et al. 2016). In a study by Zianis and Mencuccini (2003), the development and comparison of three methods for simplifying allometric equations of aboveground biomass estimation are reported. Based on the criterion of the relative difference (RD) between observed and predicted biomass data, the small trees sampling scheme (SSS) predicted quite accurate estimates for raw data reported in ten studies. The SSS equation was based on the hypothesis that information provided in published allometric equations, in conjunction with two pairs of empirical *M*-*D* values, are enough to obtain reliable predictions for aboveground stand biomass. In addition, predictions of M based on theoretical values of b were also tested with the RD criterion, but reliability of predictions in ten studies is questioned. Finally, fractal geometry was used to develop a "reductionist" model for M estimation, and implications from its implementation in biomass studies are discussed.

Usoltsev (2007) offered modern methods of estimating forest biological productivity. A number of uncertainties related to biomass and net primary productivity estimation, especially for thin root, are analyzed. A supplement in a number of 1152 plots to the database published earlier (Usoltsev 2001) with 5085 forest biomass determinations, as well as a new database involving 1098 determinations of net primary productivity, is suggested. Multiple regressions of net primary productivity are calculated, and net primary productivity age dynamics tables for spruce and pine are compiled by means of joining net primary productivity regressions with age trends of forest mensuration and biomass indices. Carbon pool (2679 Mt) and its annual deposition (165 Mt) are calculated by means of joining biomass and net primary productivity regressions with National Forest Inventory System data on the area of 127 million ha of 150 forest farms of the Ural Federal District. Corresponding maps are designed.

However, all these biomass functions belong to the regression method. They cannot claim to be a universal dependency, which can be used in a wide age range and geographic range (Usoltsev 2007; Teobaldelli et al. 2009; Stegen et al. 2011; Poorter et al. 2015).

Remotely sensed data have become the primary source for biomass estimation. The literature review by Lu (2006) has demonstrated that biomass estimation remains a challenging task, especially in those study areas with complex forest stand structures and environmental conditions. Either optical sensor data or radar data are more suitable for forest sites with relatively simple forest stand structure than the sites with complex biophysical environments. A combination of spectral responses and image textures improves biomass estimation performance (Lu 2006; Næsset and Gobakken 2008).

2.3 Study of Morphological Disturbances to Tree Trunk

Studying the influence of damages (traumas) to trunks of young trees on growth of trees and formation of forest stands is a necessary part of timber-yielding plant stud. There is always damage to trees, but the quantity of this damage sharply increases in the conditions of anthropogenous influence. The following studies are conducted to identify morphological abnormalities in young trees. Types of infringement of trunk structure are defined in comparison to characteristics of biomorphological architectural model of Rauh (Ermakova 2008). Two basic types of morphological infringements are diagnosed for a pine: infringement monopodial with preservation single-trunk and infringement monopodial with infringement single-barreled. Also, it is necessary to mark a site of the revealed morphological infringements. Result of long-term researches by Ermakova (2008) is the generalized classification of morphological disturbances. Traumatic (reparative) regeneration of trunks of a pine ordinary after damage apical meristem represents a difficult, multistage process consisting of four consecutive periods: (1) initial, destruction or damage apical runaway or a kidney with the subsequent activation and growth lateral apical meristem; (2) intermediate, reorientation in vertical position and employment of in the lead position by one or several lateral shoots; (3) stabilization, restoration monopodial branchings and stabilization single-trunk or multitrunk and restoration of rates of growth in height; and (4) formations, definitive formation of trees of morphological groups.

2.4 Mathematical Models of Trees and Forests

Modeling is a reliable tool for a theoretical study of individual trees, their populations, and ecosystems. A model predicts a crisis in the life of trees and forests; it can also identify the direction and the pace of successions (Guts and Volodchenkova 2012).

2.4.1 Forest Growth Models

Forest growth models are made for individual trees as well as the whole of a forest stand. The book by Vanclay (1994) is an introduction to the growth modeling. Examples of forest growth models can be found at Newnham (1964) and Munro (1974). Neeff and Dos Santos (2005) presented *a* comprehensive stand-level growth model for secondary forest in the Central Amazon. Verhulst's logistic model belongs to the same group. These equations are widely used in population ecology, economics, sociology, and history, where they serve to describe experimental data. The possibility of using a similar mathematical tool for a large class of systems is only made possible through the similarity of their phenomenological description, which necessarily involves the processes of birth, growth, selection, and death. Acevedo et al. (2012) described a diffusive logistic growth model to quantify forest recovery. The model consists of a diffusion term that describes the spread of forest in continuous space and time, and a logistic growth reaction that describes change in the proportion of forest. However, though pure stands have been modeled extensively and rather successfully for decades, relatively few models for mixed-species stands have been developed (Bartelink 2000). In a study by Bartelink (2000), a mechanistic tree-based model of mixed forest growth is presented. The systems of related logistic equations are convenient for analysis of joint growth of several tree species. The findings obtained in this manner present a certain interest for science (Ivanova 2014).

2.4.2 Ecological Models

Ecological models can be characterized by their degree of generality, reality, and precision. Any model, being a deliberate simplification of reality, cannot excel in all three aspects (Risch et al. 2005).

Process models and succession models are ecological models. Process models simulate the growth of trees with regard to various factors (Hope 2003). For example, Laubhann et al. (2009) investigated the influence of changing temperature, precipitation, and deposition of sulfur and nitrogen compounds on forest growth. These researchers developed an individual tree growth model with measured basal area increment of each individual tree as responding growth factor and tree size (diameter at breast height), tree competition (basal area of larger trees and stand density index), site factors (soil C/N ratio, temperature), and environmental factors (temperature change compared to long-term average, nitrogen and sulfur deposition) as influencing parameters. Succession models are the most interesting ones among them; gap models and forest landscape dynamics models are specifically noteworthy.

Gap models are based on the concept of a mosaic structure of the forest. It is assumed that mosaic structures develop relatively independently from each other and thus undergo certain stages of development. A complicated spatial structure and the presence of different phases of development ensure forest sustainability. Gap models simulate the changes in a small patch of forest on the order of 0.1 ha in size. The models project the annual growth of each individual tree on the patch as well as the death of each tree and the regeneration of new individual trees. Gap models are important because of their widespread applications in assessing the effects of environmental change on forests. The earliest such model was built by Newnham (Schlicht and Iwasa 2004). Yamamoto (2000) introduced the basic concepts of gap dynamics and summarizes major issues on gap dynamics relating to tree regeneration, with many references. Currently, these models are quite popular (Bugmann 2001; Risch et al. 2005; Kern et al. 2013). The quantitative model comparisons performed so far allow us to draw the following conclusions: (1) Gap models are quite sensitive to the formulation of climate-dependent processes under current climate, and this sensitivity is even more pronounced under a changed climate. (2) Adaptations of forest gap models to specific regions have required detailed sub-models of species life history, thus complicating model comparison. (3) Some of the complex models developed for region-specific applications can be simplified without hampering the realism with which they simulate species composition. (4) Attempts to apply the models without modification beyond the area for which they were developed have produced controversial results (Bugmann et al. 1996).

Forest landscape models simulate forest change through time using spatially referenced data across a broad spatial scale (i.e., landscape scale) generally larger than a single forest stand. Spatial interactions between forest stands are a key component of such models. These models can incorporate other spatiotemporal processes such as natural disturbances (e.g., wildfires, hurricanes, outbreaks of native and exotic invasive pests and diseases) and human influences (e.g., harvesting and commercial thinning, planting, fire suppression). The models are increasingly used as tools for studying forest management, ecological assessment, restoration planning, and climate change (Xi et al. 2009). The Hong's paper (2008) provides definitions of key terminologies commonly used in forest landscape modeling to classify forest landscape models. Modeling at the landscape scale is most relevant to quantify and understand landscape structure and dynamics (Lischke et al. 2007). Examples of these models can be found in articles by Mladenoff (2004), Wintle et al. (2005), and Lischke et al. (2006, 2007).

2.4.3 Methods of Mathematical Catastrophe Theory

The development of theoretical and methodological foundations for the identification of crisis situations in the trees and their ecosystem life is vitally important. One of the mathematical theories describing sharp changes is the catastrophe theory.

In doing so, the catastrophe theory can provide explanations for a number of phenomena, for instance, how abrupt changes in behavior can result from minute alterations in controlling factors, and why such changes occur at different control factor configurations depending on the past states of the system (Poston and Stewart 1996; Grasman et al. 2009). The catastrophe theory as a branch of mathematics began to take shape back in the mid-twentieth century. The creators of this theory are the French mathematician Rene Thom (Thom and Zeeman 1975; Zeeman 1976) and the Russian mathematician Vladimir Arnold (1992).

This theory examines general principles, which manifest themselves in different situations, and helps to better understand the mechanism of natural forces in action. Catastrophes are intermittent changes that occur as a sudden response of a system to smooth changes in external conditions (Arnold 1992). The value of an elementary catastrophe theory is that it reduces a great diversity of situations to a small number of standard schemes, which can be studied in detail. The catastrophe theory was popularized in the 1970s (Thom and Zeeman 1975; Deakin 1980; Gilmore 1993) and was promoted as a strategy for modeling in various disciplines like physics, biology, psychology, and economics (Grasman et al. 2009). However, the models chosen were only qualitative. They described generalized situations and were of little use when solving specific practical tasks. The transition to the quantitative level proved difficult. Despite all this, stochastic formulations of the catastrophe theory have been found; statistical methods have been developed to allow a quantitative comparison of catastrophe models across the data available (Cobb 1981; Cobb et al. 1983; Oliva et al. 1987; Wagenmakers et al. 2005; Grasman et al. 2009). Exciting new research based on methods of catastrophe theory emerged (Guts and Volodchenkova 2012; Ivanova 2016).

3 Study of Joint Growth of Wood Species: A Special Study

Thus, review of the literature shows that despite the huge number of publications on methods of study of woody plants, there are still many problems in the biomass of trees and forest stands. In addition, the question of the joint growth of several timber-yielding plants remains the least studied.

We conducted a special study to predict the joint growth of two species of woody plants. One of them (pine) gives valuable timber. Other wood species (birch) gives wood of poor quality and it is used mainly for firewood.

3.1 Research Area

Our research area is located in the Ural Mountains. The Ural Mountains are located on the border between Europe and Asia, at the junction of two floras (Fig. 2.1). Ural forests (Russia) are part of the belt of coniferous forests in the Northern Hemisphere.

Fig. 2.1 The Ural Mountains are located on the border between Europe and Asia

They are one of the 200 hot spots of biodiversity, the preservation of which is necessary for the future survival of mankind on the planet Earth.

The Ural Mountains are among the oldest mountains on the planet. Their history is long and complex. It begins in the Proterozoic era with the breach of the crust. This breach extended for almost two billion years, and the ocean was formed on the site of the future mountains. The convergence of lithospheric plates began about 300 million years ago, and the mountains were formed.

The research site is situated in the Zauralsky (Trans-Ural) hilly piedmont province (Middle Ural, Russia) between 57°00′–57°05′N and 60°15′–60°25′E. It is divided in foothills formed by the alternation of meridian heights and ridges (Kolesnikov et al. 1973). Absolute heights are 200–500 m above sea level. The climate is temperately cold, temperately damp. A frostless period of 90–115 days occurs, average annual temperature is +1 °C, and the average snowfall is between 40 and 50 cm (Kolesnikov et al. 1973).

3.2 Methodological Approaches

Our work is based on the methodological approach of geo-genetic (geodynamical) forest typology (Ivanova and Zolotova 2014). A geo-genetic classification is a classification based on forest origin and evolution patterns, which take into account all developmental stages of a forest ecosystem and can be used to predict future changes. We also used the approaches of soil science, forest inventory botany, and soil science in our research. To investigate time dependence, we selected sites at different stages of restoration-age shifts and then built time series out of them. Data processing was carried out using traditional statistical methods and the methods of nonlinear dynamics.

3.3 Research Objects

Pinus sylvestris **L.** This tree reaches, depending on growing conditions, a height of 45 m with a 1 m stem diameter over a period of 200 years. The crown of fully grown trees spreads with a rounded or flat top. The branching of both the stem and branches is monopodial. One shoot formed annually. The stem is cylindrical. The bark is a brownish-red color. In the upper part of the stem and in the boughs of the crown, the bark is reddish orange. The pine reaches the juvenile age between 6 and 10 years old in natural forests and between 15 and 40 years old under planting conditions. *Pinus sylvestris* reproduces solely by seed. Pollen and seeds are spread by wind. *Pinus sylvestris* is able to grow in a wide range of climatic conditions, requiring little heat; it is hardy and frost resistant, requires light, and demands very little of soil. *Pinus sylvestris* has a very ductile root system that can change direction depending on growth conditions. In deep, fresh, sandy soil, it develops a taproot and a diversity of vertical roots, whose length reaches up to 1.5 m. High ecological plasticity allows it to grow in a wide area from tundra to steppes. Scots pine is an important tree in forestry. The wood is used for pulp and sawn timber products. A seedling stand can be created by planting, sowing, or natural regeneration. Commercial plantation rotations vary between 50 and 120 years, with longer rotations in northeastern areas where growth is slower.

Betula pendula **Roth and *B. pubescens* Ehrh.** *Betula pubescens* (syn. *Betula alba*), commonly known as downy birch and also as moor birch, white birch, European white birch, or hairy birch, is a species of deciduous tree, native and abundant throughout northern Europe and northern Asia, growing farther north than any other broadleaf tree. It is a deciduous tree growing to 10 to 20 m tall (rarely to 27 m), with a slender crown and a trunk up to 70 cm (exceptionally 1 m) in diameter, with smooth but dull gray-white bark finely marked with dark horizontal lenticels. The shoots are gray brown with fine downy. The leaves are ovate-acute, 2 to 5 cm long and 1.5 to 4.5 cm broad, with a finely serrated margin. The flowers are wind-pollinated catkins, produced in early spring before the leaves. The fruit is a pendulous, cylindrical aggregate 1 to 4 cm long and 5 to 7 mm wide which disintegrates at maturity, releasing the individual seeds; these seeds are 2 mm long with two small wings along the side. It is closely related to, and often confused with, the silver birch (*B. pendula*). *Betula pendula*, commonly known as silver birch or warty birch, is a species of tree in the family Betulaceae, native to Europe and parts of Asia, though in southern Europe it is only found at higher altitudes. The silver birch is a medium-sized deciduous tree, typically reaching 15 to 25 m (tall exceptionally up to 31 meters), with a slender trunk usually under 40 cm diameter. The bark on the trunk and branches is golden-brown at first, but later this turns to white as a result of papery tissue developing on the surface and peeling off in flakes. Downy birch can be distinguished from silver birch with its smooth, downy shoots, which are hairless and warty in silver birch. The bark of the downy birch is a dull grayish white, whereas the silver birch has striking white, papery bark with black fissures. The leaf margins also differ, finely serrated in downy birch, coarsely double-toothed in silver birch. The two have differences in habitat requirements, with downy birch more common on wet, poorly drained sites, such as clays and peat bogs, and silver birch found mainly on dry, sandy soils. *Betula* is a pioneer species, readily colonizing cleared land, but later being replaced by taller, more long-lived species. The timber is pale in color with a fine, uniform texture and is used in the manufacture of plywood, furniture, shelves, matches and toys, and turnery. Both *B. pubescens* and *B. pendula* can be tapped in spring to obtain a birch sap.

We have studied the reforestation after harvest. We have studied the long joint growth of pine and birch in two variants of places of habitat:

1. Steep slopes of the southern exposition with small stony soils and very unstable water conditions. Cowberry shrub pine forests are the natural forest type (Fig. 2.2). On the tops and upper halves of the slopes of hills, humidity is most dependent on weather conditions and is highly variable. *Dicrano-Pinetum sylvestris* Preising et Knapp ex Oberdorfer 1957 grow in these conditions (Table 2.1). *Dicrano-Pinetum sylvestris* is characterized by a poor species composition of higher plants, a sparse, stunted grass-shrub level, and good natural regeneration of *Pinus sylvestris*. According to the ecological and floristic classification of these forests, they belong

Fig. 2.2 Cowberry shrub pine forests in the Ural Mountains (Russia): (**a**) general view, (**b**) soil

Table 2.1 Characteristics studied indigenous forests of the Ural Mountains

Forest type	Woody plant species	Stand composition (%)	Age (years)	Average height (m)	Average diameter at 1.3 m (cm)	Stand density (m^2 ha^{-1})
Cowberry shrub pine forests	*Pinus sylvestris* L.	90	160	24.3	40.9	35.7
	Larix sibirica Ledeb.	8–9	160	27.5	48.4	2
	Betula pubescens Ehrh., *B. pendula* Roth	1–2	100	20	21.4	0.3
Grass pine forests	*Pinus sylvestris* L.	90	150	28.9	42.4	35.5
	Picea obovata Ledeb.	1	80	10	9.5	0.25
	Betula pubescens Ehrh., *B. pendula* Roth	9	120	26.9	32.5	6.5

Fig. 2.3 Grass pine forests in the Ural Mountains (Russia): (**a**) general view, (**b**) soil

to the class *Vaccinio-Piceetea* (boreal dark coniferous and light coniferous forests) Union *Dicrano-Pinion* Matuszkiewicz 1962.

2. The lower parts of gentle slopes with thick soils (more than 50 cm) and stable water conditions. Grass pine forests grow here (Fig. 2.3). Humid, occasionally wet habitats feature pine forest *Bupleuro longifolii-Pinetum sylvestris*. In *Bupleuro longifolii-Pinetum sylvestris*, in comparison to other forest types, the signs of class *Brachypodio Pinnati-Betuletea* (boreal light-pine, small-leaved grass forests of Western, Central Siberia and the Urals) are featured in Union *Trollio europaea-Pinion sylvestris* (pine-birch forests on fertile grassy and well-enriched moisture).

3.4 Sampling Procedures

The 0.2–0.5 ha sampling plots were laid according to commonly used methods (Forest Communities Study Methods 2002). Sample plots included no less than 200 woody plants. The plots were studied with regard to their tree stand, understory, and grass layer. We counted all the trees on the sampling plot, we measured their diameter and height, and we identified the age by the annual rings.

The joint growth of pine and birch from clear-cuttings (4–5 years old) up to tree stands of 67–160 years old has been studied for these places of habitat. We have laid the 40 sample plots in forests of various ages. We studied the tree stand and young woody.

3.5 Data Analysis

Biomass in absolutely dry conditions has been used as the integral characteristic of the plant role. The mass of tree species was determined by way of calculation (Iziumsky 1972; Usoltsev 1997). We used reliable forest taxation data. The weight of the crown was calculated on the basis of regression equations that take into account physiological patterns (pipe model) (Usoltsev 1997).

In order to describe the dynamics of density (biomass) of pines (*Pinus sylvestris* L.) and birches (*Betula pendula* Roth and *B. pubescens* Ehrh.), and their mutual influence in the process of tree stand formation, we constructed models of their joint existence on the base of the systems of connected logistic equations. We used the following system of differential equations (2.1) (the Lotka-Volterra Model) (Lotka 1925):

$$\begin{aligned} \frac{dx_1}{dt} &= A_1 x_1 - B_1 x_1^2 + C_1 x_1 x_2 \\ \frac{dx_2}{dt} &= A_2 x_2 - B_2 x_2^2 + C_2 x_1 x_2 \end{aligned} \tag{2.1}$$

where x_1 is the overground mass, g/m^2 in absolutely dry condition of pines; x_2 is the overground mass of birches; and A, B, and C are parameters which are determined in the process of the solution of the inverse task. Bazykin (1985) conducted a comprehensive analysis of the models. A quantitative description of the formation of stand structure after clear-cutting is carried out in the catastrophe theory according to Bystrai methods (Bystrai and Ivanova 2010; Ivanova and Bystrai 2010). We evaluated the model parameters according to the residual functional (Eq. 2.2):

$$F(t) = \sqrt{\sum_i (Yi(t) - Yi})2 \tag{2.2}$$

Yi, statistical data; *Yi(t)*, theoretical data.

4 Joint Growth of Pine and Birch

Pine forests are indigenous forests in the Zauralsky (Trans-Ural) hilly piedmont province (Middle Ural, Russia). Highly productive stands can grow in different habitats (Table 2.1). However, the reforestation after harvesting occurs differently in different habitats (forest types) (Figs. 2.4 and 2.5).

Temporal dynamics of forest vegetation formation after clear-cutting cowberry shrub pine forest is shown in Fig. 2.4. The dynamics is studied up to 160-year-old tree stand, beginning with 5-year-old cuttings. Figure 2.4 shows clearly that pines predominate obviously by mass in all the studied interval of restoration-age changing. The difference in densities of the studied tree species is of 1–2 orders. However, the complete birch vanishing out of the structure of forming forests is not observed.

The time trends of forest vegetation formation after clear-cutting of grass pine forest in the lower parts of gentle slopes with thick (more than 50 cm) drained soils are shown in Fig. 2.4. The dynamics is dealt with up to the tree stand of 80 years old, beginning from 5-year-old cuttings. Opposite correlation of tree species densities is observed in these forest growth conditions: birches prevail, and pines are oppressed by them. Long secondary birch forests with strongly oppressed pines in the second layer are formed (Fig. 2.6).

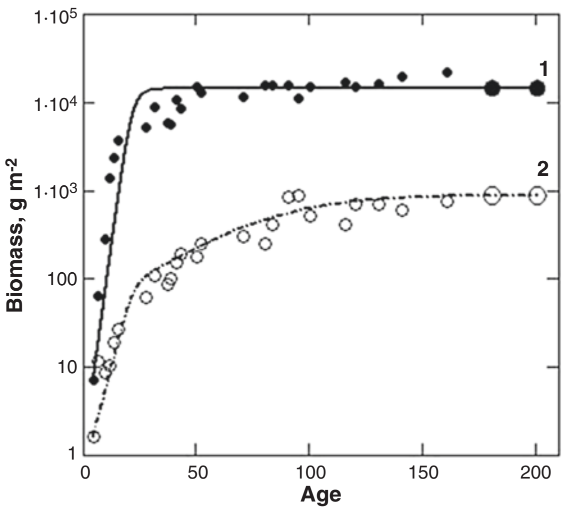

Fig. 2.4 Age dynamics of biomass of a pine (*Pinus sylvestris* L.) and birches (*Betula pendula* Roth and *B. pubescens* Ehrh.) in the steep slopes of the southern exposition with small stony soils (10–15 cm) (Ural Mountains, Russia): *1*, pine biomass (g m^{-2}); *2*, birch biomass (g m^{-2}); points, statistical data; and *lines*, the results of the solution of the system of nonlinear-dependent logistic equations. The two last points in each line indicate the prognosis for 20 and 40 years in advance. Equation coefficients: A_1 = 0.438; B_1 = 0.0000312; C_1 = 0; A_2 = 0.231; B_2 = 0.0000438; C_2 = −0.0000138

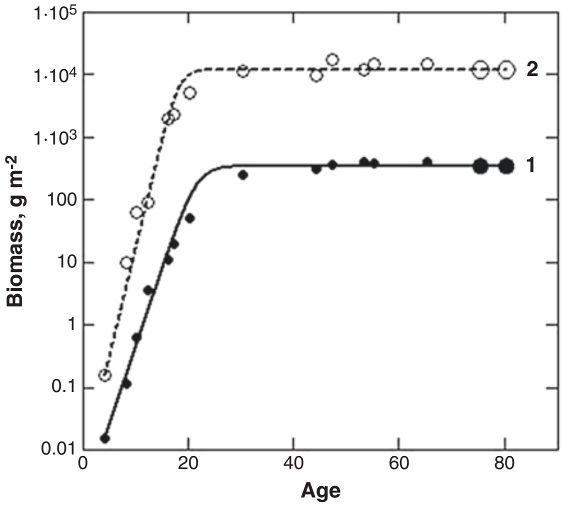

Fig. 2.5 Age dynamics of biomass of a pine and birches in the lower parts of gentle slopes with thick (more than 50 cm) drained soils (Ural Mountains, Russia): *1*, pine biomass (g m^{-2}); *2*, birch biomass (g m^{-2}); points, statistical data; and *lines*, the results of the solution of the system of dependent nonlinear logistic equations. The two last points in each line indicate the prognosis for 10 and 15 years in advance. Equation coefficients: $A_1 = 0.575$; $B_1 = 0.0017$; $C_1 = 0$; $A_2 = 0.805$; $B_2 = 0.000069$; $C_2 = 0$

Fig. 2.6 Long secondary birch forests with strongly oppressed pines in the Ural Mountains (Russia)

5 Conclusion

In conclusion, many methods for the study of timber-yielding plants exist. These methods encompass a variety of issues. They are based on traditional approaches and approaches of nonlinear dynamics. The greatest attention is paid to the study of forest stand biomass. Regression method is considered the most accurate and versatile. The set of functions is available to approximate tree biomass depending on its diameter. Allometric function is the most biologically driven. However, all these biomass functions belong to the regression method. They cannot claim to be a universal dependency, which can be used in a wide age range and geographic range. Therefore, prediction on this basis is not accurate. Logistics systems of equations are more versatile. Our research has shown that the use of systems of differential equations gives good results for the study of the joint growth of two wood species. This approach allows one to predict the role of valuable wood species in the forest stand structure in the process of reforestation. It is useful for the planning of forest management and environmental measures. However, the gap between the mathematical and experimental ecology continues to exist. The development of new universal methods of forecasting the state of timber-yielding plants and their ecosystems is still relevant.

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