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What makes a good fire? Local actor- and science-based knowledge of fuel-related functional traits of Chaco plants

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Abstract. On the basis of knowledge and values from different social actors, we investigated what biophysical properties of the wood are linked to good-quality firewood in the semiarid Chaco forest of central-western Argentina. We applied social actor-tailored semi-structured interviews to incorporate the perspectives of: a) two kinds of local social actors who carry out their productive activities in the forest (subsistence farmers and cattle ranchers), and b) ecologists. We identified plant attributes associated with the desirable or undesirable qualities after lighting firewood, and tested them through an innovative experimental game. We then calculated the fuel value index of each native woody species of the study area mentioned by local actors as a firewood source, on the basis of quantitative measurements, and compared it with their stated preference, finding partial coincidence. This is because, while the fuel value index includes some traits considered relevant, when assessing firewood quality people also consider other factors that do not intervene in this index (e.g., abundance, accessibility, effort, market preferences). The inputs from different kinds of knowledge and the implementation of qualitative and quantitative strategies gave a broader view of the valuation of plants for firewood, representing a much richer picture than that offered by each knowledge system and approach separately.

[Keywords: firewood, plant functional traits, Semiarid Chaco, Argentina, plural valuation of biodiversity, nature's contributions to people, fuel value index]

Resumen. ¿Qué hace a un buen fuego? Conocimientos de los actores locales y de la ciencia sobre los rasgos funcionales de las plantas del Chaco relacionados con el combustible. En base a los conocimientos y valores de diferentes actores sociales, investigamos qué variables biofísicas de la madera están vinculadas a la leña de buena calidad en el Bosque Chaqueño Semiárido del centro-oeste argentino. A partir de entrevistas semiestructuradas adaptadas a cada tipo de actor social, incorporamos las perspectivas de: a) dos tipos de actores sociales locales que realizan sus actividades productivas en el bosque (agricultores de subsistencia y ganaderos), y b) ecólogos. Identificamos los atributos de las plantas asociados con las cualidades deseables o indeseables después de encender leña y posteriormente los pusimos a prueba a través de un juego experimental novedoso. Luego, sobre la base de medidas cuantitativas, estimamos el índice de valor de combustible de cada especie leñosa nativa del área de estudio mencionada como fuente de leña por los actores locales y lo comparamos con su preferencia declarada, encontrando una coincidencia parcial. Esto se debe a que, si bien el índice de valor de combustible incluye algunos rasgos considerados relevantes, al evaluar la calidad de la leña también se tienen en cuenta otros factores que no intervienen en este índice (e.g., la abundancia, la accesibilidad, el esfuerzo, las preferencias del mercado). Los aportes de diferentes tipos de conocimiento y la aplicación de estrategias cualitativas y cuantitativas brindaron una visión más amplia de la valoración de plantas para leña, representando un panorama mucho más rico que el que ofrece cada tipo de conocimiento y enfoque por separado.

[Palabras clave: leña, caracteres funcionales de plantas, Chaco Semiárido, Argentina, valoración plural de la biodiversidad, contribuciones de la naturaleza a la gente]

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Introduction

Woody biomass provides >6% of the total primary energy supply worldwide, and >2 billion people depend on fuelwood and charcoal for cooking or heating (FAO 2015). In Argentina, between 2001 and 2011, native forests supplied approximately 4 million tons of raw material per year, 75% of which was destined to firewood, and 85% originated in the Chaco region (Navall 2012). Therefore, deforestation in this region, historically linked to firewood and timber extraction and cattle ranching (Bucher and Huszar 1999) and more recently to the fast expansion of the agricultural frontier (Zak et al. 2008; Fehlenberg et al. 2017) affects not only the future of the biodiversity of the region (IPBES 2018; Díaz et al. 2019), but also the livelihoods and quality of life of people who directly depend on these forests (Cotroneo et al. 2021).

To understand socioecological systems like these, interdisciplinary and transdisciplinary research approaches have been developed, recognizing contributions of different kinds of knowledge with distinct underlying epistemological frameworks (e.g., Martínez-Torres and Rosset 2014; Díaz et al. 2015, 2018). Díaz et al. (2011) proposed an interdisciplinary framework for analyzing connections between the functional diversity of ecosystems and the priorities of different agrarian social actors, using land use decisions and ecosystem services (a concept now included within the contribution of nature to people, hereafter NCP) (Díaz et al. 2018) as the main links between ecological and social systems. This implies that people perceive, value and access NCP differently, and therefore have different motivations and capacities to select, directly or indirectly, specific characteristics of the organisms, biological communities and landscapes that provide them (Cáceres et al. 2015). This selection by certain social actors can alter the provision of NCP for all social actors, through the reconfiguration of functional biodiversity (Díaz et al. 2011; Cáceres et al. 2015). This approach is compatible with the plural valuation process (Pascual et al. 2022), which seeks to make explicit the diverse values that people hold on nature and NCP, in a context of unequal access to, and distribution of the wealth generated by nature's benefits (IPBES 2019).

Values of nature vary greatly across knowledge systems, languages, cultural traditions and environmental contexts (IPBES 2022). Concerning specifically the selection of plants for firewood, previous studies have stressed that local communities appreciate certain characteristics and collection patterns according to their context (Abbot et al. 1997; Tabuti et al. 2003; Ramos et al. 2008; Thomas et al. 2011). The local perspective is often combined with the estimation of the fuel value index (FVI) (Purohit and Nautiyal 1987; Goel and Behl 1996), a quantitative way of evaluating firewood, providing a link between the characteristics measured by scientists for each species with those perceived by other people (Abbot and Lowore 1999; Rai et al. 2002; Deka et al. 2007; Ramos et al. 2008; Chettri and Sharma 2009; Cardoso et al. 2015; Márquez-Reynoso et al. 2017). However, the criteria applied by local actors in the selection of preferred species are often obscure and not fully understood in scientific terms (Chettri and Sharma 2009).

The present work focused on exploring the variables linked to good-quality firewood from the perspectives of local and scientific knowledge. First, we approached firewood through the lens of different local social actors who carry out their productive activities in xerophytic forests of the southernmost and driest extreme of the South American Gran Chaco. Then, we included the scientific perspective via two paths: a qualitative one, through the points of view of ecologists, and a quantitative one, by calculating the FVI of native species of the study area mentioned by local actors as providers of firewood.

We sought to answer the following questions: a) which are the plant functional traits and attributes linked to good-quality firewood for sale from the local and scientific perspectives? b) Are there other conditioning factors in the selection of wood for firewood besides such traits and attributes? c) Do the traits identified by different social actors match the variables used to calculate FVI? d) Is there any relationship between preferred native species and their FVI? e) What is the degree of agreement between the different local perspectives and between the local perspectives as a whole and the scientific view?

Materials and Methods

Study area

The study was carried out in rural settlements of Pocho and San Alberto

Departments, Córdoba Province, covering an area of approximately 75000 ha, between the following extreme points: Balde de la Orilla (31°19'13.00'' S - 65°36'55.00'' W) to the north; La Cortadera (31°40'01'' S - 65°22'37'' W) to the South, La Guanaca (31°29'50.55'' S - 65°39'30.17'' W) to the west; and Sierra de Pocho (31°35'12.23'' S - 65°18'1.61'' W) to the east. The most important rural settlement in this area is Chancaní (31°24'57.87'' S - 65°27'4.13'' W). The climate is subtropical with a historical mean annual precipitation of 500 mm concentrated in spring-summer (October-March) and a mean annual temperature of 18 °C (Cabido et al. 1994; Carranza and Ledesma 2005). This area was originally covered by an open xerophytic forest with a canopy dominated by *Aspidosperma quebracho-blanco* and *Neltuma* spp., and an understorey dominated by *Mimozyganthus carinatus*, *Senegalia gilliesii*, *Celtis ehrenbergiana* and *Larrea divaricata* (Cabido et al. 1994). Today, the study area consists of a mosaic of different ecosystems, ranging from forests to open shrublands or cultivated patches, with a very small proportion of primary forest, as a result of a combination of different historical and present livestock grazing, logging and cultivation regimes (Conti and Diaz 2013; Hoyos et al. 2012). In the first decades of the 20th century, large-scale forestry exploitation provided the energy (charcoal and firewood) and timber needed in more developed agro-exporting regions of the country (Silvetti 2010). In recent years, the expansion of the agricultural frontier over native ecosystems triggered the displacement of cattle ranching to more marginal areas, including the study area (Cáceres et al. 2020). These changes meant that between 1970 and 2000, more than 1 million ha of Cordoba's seasonal dry forests were lost, with deforestation rates similar or even higher than those recorded in tropical forests (Zak et al. 2008). Deforestation continued between 2000 and 2020 in Cordoba province, reaching a loss of around 400000 ha (FAUBA et al. 2023).

Social actors involved

Within the local perspective, we focused on the knowledge of two types of social actors who carry out their mixed production activities in the area: subsistence farmers and cattle ranchers. Subsistence farmers are small farmers whose main activity is extensive livestock raising (mostly goats) and also using native vegetation for firewood, timber and non-timber products (Cáceres et al. 2020; Cáceres and Tapella 2022). Within this group, tasks are traditionally divided between men and women. Men are in charge of cattle in the fields, farms, forestry activities and alternative off-farm work, while women are responsible for managing goat herds and other peridomestic activities (Silvetti 2010; Tapella 2012). Specifically related to the exploitation of the forest for the production of firewood and charcoal, men have traditionally been the workforce, while some women worked in the bagging of these products. Cattle ranchers are devoted to semi-intensive cattle ranching and, in some cases, the production of firewood and charcoal for non-local markets (Silvetti 2010; Tapella 2012). This group has not had a direct work link with forestry activities other than through hiring subsistence farmer labor to obtain firewood, charcoal or timber. Traditional production of firewood and charcoal for sale is only exceptionally done today, partly due to current government regulations and to deforestation and forest degradation (Tapella 2012). Finally, it should be noted that during the interviews the producers were asked to distinguish their personal assessment of firewood from those made by firewood traders. Regarding the scientific perspective, we focused on researchers specialized in ecology, with specific knowledge of functional diversity, but whose research was not related to the study area or to the local knowledge of the aforementioned social actors.

Data collection

The data collected in previous studies carried out in the same territory and addressed to the same social groups (Silvetti 2010; Tapella 2012) facilitated the design of a semi-structured interview adapted to be understood by each of the different social actors. We designed two different draft interviews, one for local actors and another for researchers. We then pilot tested them (in the case of local actors, we tested it separately with subsistence farmers and cattle ranchers). This allowed us to assess the interview's ability to answer the kind of questions addressed in the research, and to tailor it specifically to the different actors participating in the research. These pilot interviews were conducted before the formal start of the fieldwork, and the responses of the interviewees were not considered as part of the research results informed in this article. The individuals belonging to each of the local actor groups to be interviewed were selected on the basis of consultation with key informants; from there, chain referrals were followed (Huntington 2000; Atkinson and Flint 2001).

We interviewed 30 subsistence farmers. As a consequence of gender division in the production of plant-based fuels (see above) and the predisposition to be interviewed, most of the participants were men (90%) and a smaller proportion were couples of men and women (6.6%), with only one head-of-household woman interviewed (3.3%). We also interviewed 10 cattle ranchers, all of them men because no women were found to belong to this group (see above). The selection of more subsistence farmers than cattle ranchers was due to the fact that they are the most numerous farmer group in the area (Cáceres et al. 2015). Finally, 10 ecologists were interviewed, 60% of them women and the rest men, after seeking gender parity in conjunction with the possibility to conduct the interviews at times of the COVID-19 pandemic. The age of all interviewees was between 25 and 80 years. Key informants were identified within each group, based on the recognition by others in their communities as being knowledgeable about the subject in the case of local actors, or for having investigated issues related to plants traits in the case of ecologists (Marshall 1996).

The interview was divided into two parts. In the first part, we asked what makes a good fire and the characteristics of the plants —functional traits and states, or attributes, of those traits that made them of higher or lower quality, which species were preferred and whether other factors conditioned their use. The second part was based on a qualitative experiment called the Wood Classification Game (WCG), in order to test the wood traits and attributes that emerged during the conversations. The idea was to stimulate interviewees to think in terms of functional traits and not to resort to their previous knowledge of a particular species. The game consisted of asking the interviewees to group unlabeled slices of wood according to their quality as firewood (good, regular or bad) and give reasons for their classification. Eighteen tree and shrub species were included (Table 1): 13 native species of the study area (western Semiarid Chaco, NW of Córdoba), including those most abundant in the vegetation of the area (Conti and Díaz 2013), and 5 non-native species of the study area. The set of wood slices included a range of densities, colors, and origins, and, in order to make it difficult to recognize the species by their external features, they had the bark removed (Supplementary Material-Figure S1). Each native species was rated as good, regular or bad according to the highest classification frequency for each social actor.

Field work followed the International Society of Ethnobiology Code of Ethics (ISE 2006). During the first visit, we introduced ourselves and communicated the objectives of our research and then we agreed a second visit to do the interview. The ecologists were contacted by email and later interviewed in person. Each interview lasted 45-90 minutes and was recorded digitally.

Species selection, sampling and measurement of functional traits

For the wood physical analysis, we collected samples of 13 native species of shrubs and trees during the winter (dry season) of 2019, from tertiary branches of >2 cm diameter of 3 randomly chosen individuals of each species, following the protocols for wood density measurement by Pérez-Harguindeguy et al. (2013) (Table 1). The samples were cold-stored in sealed and labeled plastic bags until measured in the laboratory.

To calculate the fuel value index (FVI), we measured moisture, density, ash content and calorific value. First, we weighed fresh samples and determined their fresh volume using the water displacement method (Pérez-Harguindeguy et al. 2013). Then, we dried them in a hot air oven at 100 °C until constant weight in order to determine the moisture content. We determined wood density as the ratio between the dry weight and the fresh volume. For ash determination, we burned a 2 g dried and ground sample in a muffle furnace at 550 °C for 5 h (Goel and Behl 1996). To determine the calorific value, we dried each powdered sample at 103±2 °C until constant weight and then pressed it into 1 g of pellets. A Parr® oxygen bomb calorimeter, model 1341, with oxygen at 25 atm was used for this purpose. Finally, we calculated the fuel value index following Purohit and Nautiyal (1987) as follows:

$$\text{FVI} = [\text{calorific value (kJ/g)} \times \text{density (g/cm}^3)] / [\text{ash fraction (g/g)} \times \text{water content (g/g)}]$$

Data analysis

We analyzed the interviews using thematic coding analysis (Robson and McCartan 2015).

Table 1. Species and their characteristics used in the Wood Classification Game (WCG) and preference frequencies by each local social actor. Scientific nomenclature follows the Catálogo de Plantas Vasculares del Cono Sur (2022). Origin: native of the study area (N) or non-native of the study area (NoN). NA: not applicable. Classification according wood density follows Suirezs and Berger (2010): very light (0.100-0.350 g/cm^3); light (0.351-0.550 g/cm^3); semi-heavy (0.551-0.750 g/cm^3), heavy (0.751-1.000 g/cm^3) and very heavy (>1.000 g/cm^3), with densities retrieved from Atencia (2003), Giménez and Moglia (2003), Conti (2012), Walia (2013) and Çavuş et al. (2019).

Tabla 1. Especies y sus características utilizadas en el Juego de Clasificación de Maderas y frecuencias de preferencia por cada actor social local. La nomenclatura científica sigue el Catálogo de Plantas Vasculares del Cono Sur (2022). Origen: nativo del área de estudio (N) o no nativo del área de estudio (NoN). NA: no aplica. La clasificación según la densidad de la madera sigue a Suirezs y Berger (2010): muy ligera (0.100-0.350 g/cm^3), ligero (0.351-0.550 g/cm^3), semipesado (0.551-0.750 g/cm^3), pesado (0.751-1.000 g/cm^3) y muy pesado (>1.000 g/cm^3), con densidades tomadas de Atencia (2003), Giménez y Moglia (2003), Conti (2012), Walia (2013) y Çavuş et al. (2019).

Scientific name	Vernacular name	Growth form	Origin	Categorical wood density classification	Color	Preference frequency (%) subsistence farmers	Preference frequency (%) cattle ranchers
Aspidosperma quebracho-blanco Schltdl.	Quebracho blanco	tree	N	heavy	Yellowish white, little difference between alburnum and duramen.	100	100
Celtis ehrenbergiana (Klotzsch) Liebm. var. *ehrenbergiana*	Tala	shrub/tree	N	heavy	Yellowish white, no difference between alburnum and duramen	-	-
Condalia microphylla Cav.	Piquillín	shrub	N	heavy	Dark reddish duramen, small light brown alburnum	40	40
Geoffroea decorticans (Gillies ex Hook. and Arn.) Burkart	Chañar	Tree	N	semi-heavy	Yellowish white, no difference between alburnum and duramen		
Larrea divaricata Cav.	Jarilla	shrub	N	heavy	Ocher yellow background and dark brown rings duramen, small ocher yellow alburnum	50	40
Mimozyganthus carinatus (Griseb.) Burkart	Lata	shrub	N	heavy	Yellowish white alburnum, brown duramen	53	70
Neltuma flexuosa (DC.) C.E. Hughes and G.P. Lewis	Algarrobo negro	tree	N	heavy	Little yellowish white alburnum, brown to reddish brown duramen.	100	100
Parkinsonia praecox (Ruiz and Pav. ex Hook.) Hawkins	Brea	shrub/tree	N	semi-heavy	Light yellow ocher no difference between alburnum and duramen	-	-
Sarcomphalus mistol (Griseb.) Hauenschild	Mistol	tree	N	heavy	Yellowish white laburnum, light reddish brown small duramen	-	-
Schinopsis lorentzii (Griseb.) Engl.	Orco quebracho	tree	N	very heavy	Reddish brown duramen	-	-
Senegalia gilliesii (Steud.) Seigler and Ebinger	Garabato	shrub/tree	N	very heavy	Yellowish small alburnum and purplish brown duramen turning black	-	-
Strombocarpa torquata (Cav. ex Lag.) Hutch.	Tintitaco	shrub/tree	N	very heavy	Dark reddish duramen, small light brown alburnum	57	40
Vachellia aroma (Gillies ex Hook. and Arn.) Seigler and Ebinger	Tusca	Shrub/ tree	N	heavy	Yellowish white small alburnum, reddish brown duramen.	-	-
Anadenanthera colubrina (Vell.) Brenan var. *cebil* (Griseb.) Altschul	Cebil	tree	NoN	heavy	Pinkish brown duramen	NA	NA
Jacaranda mimosifolia D. Don	Jacarandá	tree	NoN	semi-heavy	Yellowish white, alburnum and duramen indistinguishable	NA	NA
Morus nigra L.	Mora	tree	NoN	light	Yellowish white alburnum, brown duramen	NA	NA
Prunus persica (L.) Batsch var. *persica*	Durazno	shrub/tree	NoN	semi-heavy	Light pinkish brown duramen	NA	NA
Salix humboldtiana Willd. var. *humboldtiana*	Sauce	tree	NoN	light	White to pinkish white, alburnum and duramen indistinguishable	NA	NA

The criterion for the inclusion of a category in the analysis was that at least 25% of the interviewees or a key informant within each social actor group had mentioned it during the interview. We calculated the preference of a species for firewood as the frequency of respondents mentioning it (Ramos et al. 2008; Cardoso et al. 2015), with the same criterion of inclusion as above (>25%). Regarding the WCG, we calculated the relative frequency of each option (good, regular, bad) for species by each social actor, and plotted it with matplotlib 3.5.0 (Hunter 2007; Caswell et al. 2021) on Python 3.9.7 (Python Software Foundation 2020).

To statistically analyze whether different social actors classified the wood slices in a similar manner or not, we run a multiple correspondence analysis (MCA) on a matrix made with each interviewee's result achieved in the WCG. MCA was done in R with the FactoMineR 2.4 (Le et al. 2008) package and plotted with ggplot2 3.3.5 (Wickham 2016). We evaluated the effect of the social actor category on the classification with a PerMANOVA test on a Gower's distance matrix after confirming the homogeneous dispersion within each group. PerMANOVA and the analysis of multivariate homogeneity of group dispersions were conducted with cluster 2.1.2 (Maechler et al. 2021) and vegan 2.5-7 (Oksanen et al. 2020) packages and plotted with ggplot2 3.3.5 (Wickham 2016). Finally, we conducted the statistical analyses of FVI on R 4.1.2 (R Core Team 2021) with packages stats (R Core Team 2021), car (Fox and Weisberg 2019) and multcompView 0.1-8 (Graves et al. 2019), and then plotted with matplotlib 3.5.0 (Hunter 2007; Caswell et al. 2021) on Python 3.9.7 (Python Software Foundation 2020).

Results

Good firewood and preferred species

When asked what good-quality firewood was like, subsistence farmers and cattle ranchers began by naming the species they considered good or bad as firewood, since it was difficult for them to directly describe the traits and attributes without referring to specific species known to them. They were then asked to compare the most contrasting species to advance in the description of what makes a good fire, that is, what the desired or undesirable qualities of the wood are once lit. From this, it was possible to go deeper into what traits and attributes were associated with a good fire. Subsequently, they were asked to mention the preferred species as firewood for sale and the reasons for their choices. In addition, during the interview, other factors emerged that affected firewood choices, regardless of its quality.

In contrast, the ecologists mentioned first the functional traits and attributes of the wood and the undesirable or desirable qualities once lit, and then proceeded to the more practical knowledge, where they had greater difficulty in trying to imagine themselves in the activity of producing firewood. It should be mentioned that native species named by local actors were, by study design, not familiar to ecologists. Therefore, researchers did not mention data in this regard.

Out of a total of 13 native firewood species mentioned, only six were indicated as being preferred for commercial purposes by local actors (Table 1). The species with the highest preference values for both local actors (100%) were the *Neltuma flexuosa* and *Aspidosperma quebracho-blanco trees.* They were followed by four shrub species ranging from 40% to 70% preference: *Strombocarpa torquata*, *Mimozyganthus carinatus*, *Larrea divaricata* and *Condalia microphylla.* In the case of shrubs, participants often mentioned that their preference was subject to finding individuals with enough thick sticks.

The evaluation of the quality of the firewood was divided into three categories. The first one, 'qualities after lighting' includes the desirable or undesirable qualities of firewood once lit. It was necessary to make these qualities explicit first to identify the traits and attributes that are associated with them. Thus, the second category is called 'traits before lighting', which refers to the traits and attributes of woody plants that are distinguishable before lighting the fire (Table 2). Finally, the third category is 'firewood handling'. Here, the interviewees included other considerations irrespective of the plant's quality attributes as fuel.

Within the category of 'qualities after lighting', local actors defined good quality firewood as one that generates more abundant and durable embers and emits good heat. Ecologists, in agreement, mentioned durability or slow combustion and calories or calorific value as properties of good quality firewood. They also added the idea of flammability

Table 2. Relationships between traits and attributes of woody plants used as firewood, and the desirable and undesirable qualities after lighting, according to local social actors (subsistence farmers and cattle ranchers) and ecologists. *Pointed out as an important quality, but with no linked trait.

Tabla 2. Relaciones entre los rasgos y atributos de las plantas leñosas utilizadas como leña con las cualidades deseables e indeseables después del encendido, según los actores sociales locales (agricultores de subsistencia y ganaderos) y los ecólogos. *Señalado como una cualidad importante, pero sin rasgo vinculado.

	Desirable qualities					Undesirable qualities	
	Good heat/ calorific value	Ember durability/ slow combustion	Ember amount	Ease of ignition/ flammability	Odor	Spark emission	Smoke emission
Subsistence farmers	Dry weight: heavy	Dry weight: heavy	Dry weight: heavy		Depends on the species	Depends on the species	
		Hardness: hard		Hardness: not too hard			
		Stick diameter: thick	Stick diameter: thick	Stick diameter: thin			
				Water content: dry			
Cattle ranchers	*	Dry weight: heavy			Depends on the species	Depends on the species	
		Hardness: hard		Hardness: not too hard Stick diameter: thin			
		Stick diameter: thick	Stick diameter: thick				
				Water content: dry			
Ecologists	Wood density (weight: heavy and hardness: hard	Wood density (weight: heavy and hardness: hard)		Hardness: not too hard	*	*	*
			Stick diameter: thick	Stick diameter: thin			
				Water content: dry			

as a desired quality. Regarding undesirable qualities, the three social actors mentioned the generation of sparks and unpleasant odors as negative, and the local actors linked them to the particularities of each species. Only ecologists indicated smoke emission as negative.

In the second category, 'traits before lighting', subsistence farmers considered the weight of the wood to be one of the important traits for distinguishing good quality firewood *a priori*. They mentioned that a dry heavy wood translates into a good amount of ember that will last longer once lit and will emit good heat. They recognized two factors that affect the weight of the wood. The first is the water content, which decreases with time once a piece of wood is cut. That is why they prefer to estimate the weight with seasoned wood, in addition to the fact that in this state it is easier to light. The water content depends on whether it is extracted from a living or dead tree or branch, on the species that is being felled and on the season when it is felled. The second factor that affects the weight of the wood is related to sanitary condition. When the wood is healthy, it is heavier, which influences the amount and durability of ember. Another attribute to generate good-quality ember is high hardness, which also translates into greater ember durability. However, as a disadvantage, hard or very hard wood takes longer to light. Weight and hardness usually go hand in hand, but the weight is more important than hardness as an indicator.

Cattle ranchers also mentioned high weight and hardness as important attributes, but they only related them to ember durability. Besides, they recognized water content and sanitary condition of the wood as factors with the same influences described above.

Both local social actors mentioned the concept of 'heart', which combines a series of attributes of wood. The heart represents duramen, and a 'good heart' wood has a hard heart, which differs from alburnum in its darker color, and has a higher duramen/alburnum ratio. Thus, the heart has attributes that characterize good quality firewood, but it is also an indicator of good quality wood for other uses, such as for fence posts. In addition, the color of the heart of each species is useful for its identification by local actors.

Ecologists linked the density of the wood with the quality of the ember. The indicators of wood density for this group are the hardness and weight of the wood. (i.e., a high hardness or weight indicates high density). So, a dense stick transforms into embers with greater durability and calorific value, but at the same time, high wood density translates into greater difficulty in lighting. Because of this, some ecologists considered very hard or very heavy woods undesirable, preferring an intermediate wood density for the provision of this NCP. Additionally, researchers generally associated hard and heavy woods with those with dark duramen, as local actors did when speaking of the heart, although neither kind of actor considered color alone a determinant factor. Regarding the state of the wood, ecology researchers preferred dry wood to facilitate its ignition.

Another important trait that emerged was the diameter of the stick. Both local actors and ecologists recognized that a small-diameter stick (in local terms, 'thin stick size') serves to light the fire, while one with larger diameter (in local terms, 'thick stick size') is related to a greater amount and durability of the ember, particularly when it is combined with other important traits such as weight and hardness.

Concerning the 'firewood handling' category, subsistence farmers and ecologists valued as negative the presence of many spines. Furthermore, ecologists linked the attributes of good quality attributes with large trees, but when they visualised themselves personally cutting and collecting firewood, they preferred smaller trees that are more easily handled or to collect fallen deadwood.

Finally, ecologists mentioned the preference not to fell a living tree and/or an entire tree, and instead cut down a sick or old one, or remove dry branches, to minimize damage to the forest and favor regeneration. They also stressed the importance of considering the forest as a system and preserving its ecosystem properties. The 'irrationality' of cutting down saplings is a point in common between the scientific and local perspectives, since it is justified neither by the yield nor by the damage it causes to the forest by not allowing its renewal. Additionally, local actors argued that it is necessary to cut dry or sick branches to allow the resprouting of the trees and stop the spread of pests.

Wood Classification Game: Relevant traits and attributes for good quality firewood

Figure 1 shows the classification of wood slices by each social actor, as a result of the WCG. Statistically, there were no differences in the classification made by each social actor (Supplementary Material-Figure S2). In general, the three social actors classified light and semi-heavy woods as bad, and the heavy and very heavy ones as regular and good. Ecologists valued the wood slices as regular in a greater proportion than the rest of the actors, which could be due to a lack of direct experience in forestry activities and lack of knowledge of the native species' characteristic color patterns. The criteria applied to classify the wood slices by each social actor belonged to the 'traits before lighting' category. The three groups (>95% for each group) based their classification on the weight of the wood slice in relation to its volume (i.e., a rule of thumb for wood density), ratifying the high importance given to this trait in the interviews. Among local actors, 50% of cattle ranchers and 37% of subsistence farmers considered the presence of 'heart' in the wood as a second criterion. Both tried to recognize woods based on the heart, specifically its color. During the WCG, they considered the heart to assess the health of the wood, despite the fact that this aspect was standardized in all the slices (i.e., all the slices were in excellent sanitary condition).

In addition to weight as an indicator of wood density, the second most important criterion for ecologists (40%) was the color of the wood. However, it is worth noting that color is a criterion ratified or rectified on the basis of weight, both in the case of researchers and local actors. A third criterion, mentioned by researchers (30%) is the space between growth rings. They mentioned that this criterion would indicate whether the growth of the plant is slow or fast, depending on whether the rings are closer together or further apart, respectively; this in turn would indirectly indicate higher or lower wood density. Nevertheless, it was not applied by them due to the difficulty of determining it with the naked eye.

Fuel value index of native species

The fuel value index combines some of the desired qualities recognized by the actors in this study (calorific value) with the traits mentioned to affect these qualities (density and water content). Concerning the mass fraction, the reference to ash was linked to the rate at which the plant material was consumed, rather than the amount of ash remaining after consumption. Thus, this speed of consumption was another way of expressing the importance of the durability of the ember.

FVI values significantly differed among species, with a 5-fold difference between the species with the highest and lowest

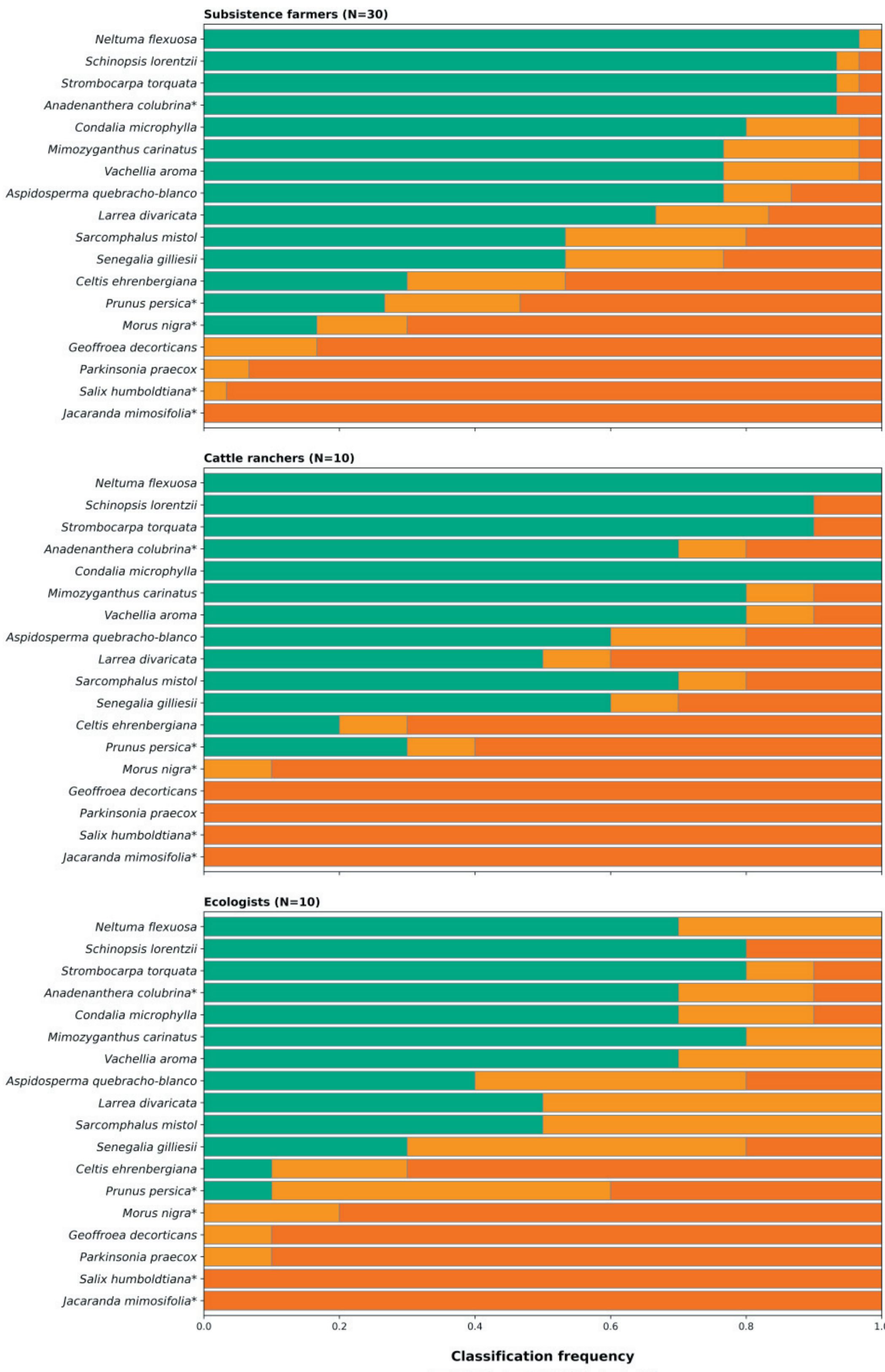

Figure 1: Legend on next page

Figura 1: Leyenda en la página siguiente

Figure 1. Classification of wood slices of different species into different categories of firewood quality, on the basis of the frequency in which each species was included in the good (green), regular (light orange) or bad (dark orange) category in the Wood Classification Game. The species are ordered from highest to lowest classification frequency within the 'good' category for subsistence farmers. The order of species is repeated for the classifications according to other social actors to ease comparison. *Non-native species of the study area.

Figura 1. Clasificación de las rodajas de madera de diferentes especies en las distintas categorías de calidad de leña, basada en las frecuencias con las cuales cada especie fue incluida en la categoría 'buena' (verde), regular (naranja claro) o mala (naranja oscuro) en el Juego de Clasificación de las Maderas. Las especies están ordenadas de mayor a menor frecuencia de clasificación dentro de la categoría 'buena' para los agricultores de subsistencia. El orden se repite para las clasificaciones de los otros actores sociales para facilitar la comparación. *Especie no nativa del área de estudio.

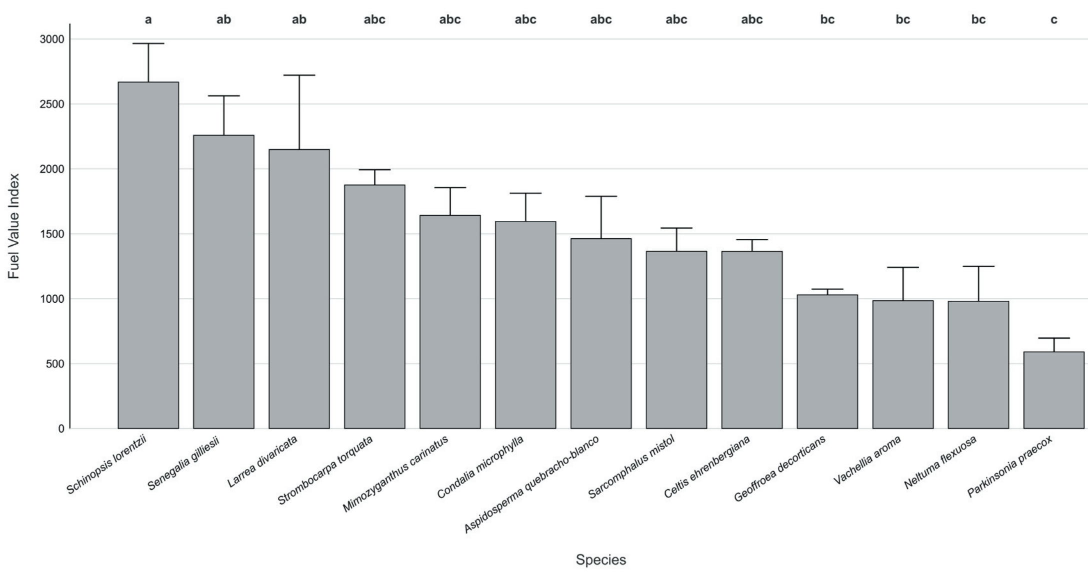

Figure 2. Fuel value index of 13 native species of the study area used as firewood in the Semiarid Chaco Forest (central-western Argentina). Bars represent species means, and whiskers the standard errors. Different letters indicate significant differences according to Tukey's test at $P<0.05$.

Figura 2. Índice de valor combustible de 13 especies nativas del área de estudio utilizadas como leña en el Bosque Chaqueño Semiárido (centro-oeste argentino). Las barras representan las medias de las especies y los bigotes los errores estándar. Letras diferentes indican diferencias significativas según la prueba de Tukey, $P<0.05$.

values (Figure 2). Accordingly, species are distributed staggered in this range, which causes statistically significant groups to overlap; only *Schinopsis lorentzii* (highest value) differed completely from *Parkinsonia praecox* (lowest value).

Discussion

We found that different social actors assessed firewood quality through different thought processes. Subsistence farmers and cattle ranchers made a path from the particular to the general through their responses. As a starting point, they mentioned the good and bad species for firewood based on their knowledge of their local context, illustrating the context-specific approach to NCP (Díaz et al. 2018). They then described the desired attributes and qualities for a good fire, and used them to justify the preference of certain species over others. In contrast, ecologists moved from abstraction to placing themselves in the local context. They started from the functional traits and attributes that are linked to the quality of the firewood in any situation (consistent with the generalizing perspective on NCP) (Díaz et al. 2018), to later think about the choices they would make for the firewood production activity. By imagining themselves in the context of the activity, they described the selection and collection associated with domestic use of firewood; that is, with the experience they had as users.

The context-specific perspective from which local actors started and the generalizing perspective from which researchers did, met in the WCG. This game allowed them to ratify, rectify or expand what had been said during the interview. Overall, it proved highly useful in building bridges between knowledge systems: it facilitated the emergence of traits and attributes in those cases where abstract thinking of traits independently of specific species was challenging for the local interviewees. It also allowed ecologists to assess different types of wood slices even though, as mentioned above, they were unaware of the performances of native species. It made it easier for all actors to test their perceptions and knowledge about the traits and attributes identified as important during interviews, and contributed to finding analogies between the categories 'before lighting' and 'after lighting' categories. Finally, it added a ludic component that increased the interest of the meeting for the actors.

What makes a good fire according to different social actors?

The main novel contribution of our study with respect to the pre-existing literature is that the focus was on linking plant species traits and attributes 'before lighting' with their desirable or undesirable qualities as firewood ('qualities after lighting'). This provides new insight into the selection of plants made by different social actors, regardless of the species identity and the experience in using firewood.

Both local social actors and researchers agreed on the 'qualities after lighting' of the firewood. These qualities coincide with those reported in previous studies: ease of ignition or flammability (Tabuti et al. 2003; Deka et al. 2007; Ramos et al. 2008; Martínez 2015; Jiménez- Escobar 2021); good heat or calorific value and its maintenance over time (Tabuti et al. 2003; Deka et al. 2007; Ramos et al. 2008; Morales et al. 2017; Martínez 2015; Jiménez-Escobar 2021), and high ember amount and durability (Abbot et al. 1997; Tabuti et al. 2003; Deka et al. 2007; Ramos et al. 2008; Cardoso et al. 2015; Martínez 2015; Morales et al. 2017; Jimenez-Escobar 2021). All actors coincided, and agreed with previous studies in other areas, on the undesirability of unpleasant odor (Ramos et al. 2008; Martínez 2015) and spark emission (Tabuti et al. 2003; Deka et al. 2007; Ramos et al. 2008). Another undesirable quality was the emission of heavy smoke, also mentioned in a number of previous studies (Tabuti et al. 2003; Deka et al. 2007; Ramos et al. 2008; Martínez 2015; Morales et al. 2017; Jimenez-Escobar 2021), but here it was considered only by the ecologists.

Subsistence farmers assigned 'before lighting' traits and attributes to all the 'after lighting' qualities described by them, except for spark emission and odor. These undesirable qualities are directly attributed to certain species, rather than being associated with specific traits or attributes. Cattle ranchers almost completely coincided with subsistence farmers, except for the absence of mentions to traits and attributes linked with good heat. Ecologists related the qualities to different traits and attributes, except for those that they recognized as undesirable, such as odor, spark and smoke emission.

In addition, our study revealed factors related to the state of the wood that have an indirect impact on the qualities of the firewood, such as the health of the wood and water content. Wood health is widely mentioned among local actors, because the main tree health problems in the area are related to the presence of xylophagous insects, specifically beetles in the Bostrychidae, Cerambycidae and Buprestidae families (Karlin et al. 2013). A case in point is *Neltuma flexuosa*, a tree that provides multiple NCP and is attacked by *Torneutes pallidipennis*, affecting the quality of its wood (Ferrero et al. 2013). The water content of the wood affects the perception of weight, in addition to influencing its flammability.

Additional elements are considered in the evaluation of firewood by all social actors. One of them is related to effort: for researchers it involves the ease of splitting the wood and gathering firewood, factors that have also been described in other studies (Abbot et al. 1997; Tabuti et al. 2003; Ramos et al. 2008). In the case of subsistence farmers, it implies generating more profit per unit of work time, given the great physical effort it involves. For both actors, high spininess is a negative attribute, also in coincidence with previous studies (Tabuti et al. 2003).

Finally, forest conservation appeared as a shared criterion between local actors and ecologists. The former, focusing on a renewal that allows sustaining the NCP on which they depend, and the latter, trying to preserve the properties of the ecosystems. It should be noted that these traits and attributes are associated with firewood aimed to the market. Other destinations, such as domestic use, can change preferences and what is considered negative or positive (Jiménez-Escobar 2021).

Preferences and quantitative fuel value

We evaluated how well the stated preferences for native species matched their quantitative value as fuel, as measured by the FVI. We found partial coincidence, in agreement with some previous studies (Rai et al. 2002), although coincidences (Ramos et al. 2008; Cardoso et al. 2015) and discrepancies (Márquez- Reynoso et al. 2017) have both been reported.

Within the six highest FVI values, there are species assigned as 'good' in the WCG, and four of the six species are preferred by local actors. However, the two highest FVI values, corresponding to *Schinopsis lorentzii* and *Senegalia gilliesi*, are not preferred species. In the case of *Schinopsis lorenztii*, it responds to four reasons: First, this species is restricted to certain areas of the territory, so it is not available to everyone. Second, those who had experienced burning this species did not consider it to be good firewood due to some undesirable qualities (spark emission, difficult to ignite, embers that break into small pieces as they burn). Third, this species is more valued as posts for fences, corrals and paddocks. Fourth, its wood is very hard, involving much effort, especially considering that an axeman gets paid per cubic meter of chopped wood rather than per hour worked. Therefore, local actors prioritized species with lesser logging effort. As for *Senegalia gilliesii*, it is a shrub with thin branches and very thorny, so despite its high FVI, its use is not justified due to its low yield.

The next four FVI values in descending order correspond to *Larrea divaricata, Strombocarpa torquata, Mimozyganthus carinatus* and *Condalia microphylla*. All these species are recognized for having good weight and hardness, but because they are mostly shrubby, they only serve as embers when their branches go beyond a certain thickness (Cardoso et al. 2015). In general, shrubs are mostly used for domestic fuel, such as for boiling water or bread baking.

A species with positive and negative qualities as firewood is *S. torquata.* On the one hand, local actors highlighted its weight and hardness, higher than those of most other native species. On the other hand, they identified it as emitting a large number of sparks and being difficult to cut or light. In addition, like *S. lorentzii*, this species is a much more valued as posts.

Further down in the rank of FVI values, there are four species assigned as 'good' and three as 'bad' in the WCG. Among the good ones, there are two species with absolute preference: *Aspidosperma-quebracho blanco* and *Neltuma flexuosa*. It is worth noting that the FVI value of *A. quebracho-blanco* was not significantly different from those of species at the higher or lower send of the rank (*S. lorentzii* and s *Parkinsonia praecox*, respectively). *Neltuma flexuosa* showed no statistical difference with a wide range of species from *Larrea divaricata* to *P. praecox*. The choice of *A. quebracho-blanco* and *N. flexuosa* by local actors is based on their vast experience in the use of native species as firewood and/or charcoal; they point out that both species are the ones that best meet the desired qualities after lighting. They also mention that both species have features related to these qualities, such as being large trees, providing heavy, thick and hard sticks that translate into higher yields. In addition, the market demand for these species is consistent with this preference by local actors (or vice versa). Martínez (2015) described similar results for the Chaco Serrano forest in the same province, where subsistence farmers appreciate hard, strong and durable firewood, especially from large native trees. The main difference highlighted between *A. quebracho-blanco* and *N. flexuosa* by local actors is that *A. quebracho-blanco* is not attacked by xylophagous insects that alter the quality of the wood, and that *N. flexuosa* is particularly abundant (high availability).

The other species assigned as 'good' are *Sarcomphalus mistol* and *Vachellia aroma*. Although the FVI value of *S. mistol* did not differ from those of species across the entire range, it is not preferred. That is because its presence is restricted to certain areas of the territory and in a small number of individuals, limiting its availability for all local actors, so its quality as firewood is often unknown. In addition, it is highly appreciated for its nutritious fruits as fodder or food. *Vachellia aroma* only differs from the highest value of FVI and, like other shrubs, it tends to have thin branches, so it is usually used for domestic requirements, such as starting fires or for cooking with flame.

The three species rated as 'bad' were *Celtis ehrenbergiana, Geoffroea decorticans* and *Parkinsonia praecox*. Their slices were described as light and heartless, and the three species were considered 'burners' by local actors, which means that they produce abundant flames, but no embers. Although *C. ehrenbergiana* is ubiquitous and locally abundant, it often adopts a shrubby habit that limits its yield/effort ratio. Finally, the FVI of *P. praecox* does not statistically differ from those of most of the preferred species; however, it is quite often named to define everything that is unwanted in terms of firewood, and is perceived as a useless plant in general. Here, the absolute FVI is in accordance with local actors' preferences.

In summary, although 'traits before lighting' and 'qualities after lighting' had partial coincidence with the parameters involved in the estimation of the FVI, this index was insufficient to determine wood quality for firewood. Other factors also determine social-actor preferences. Local actors have recognized the local Semiarid Chaco forest in general as a 'good forest' because it provides multiple NCP, especially for subsistence farmers (Cáceres et al. 2015; Cáceres and Tapella 2022). The deterioration of these forest ecosystems due to long-term and recently intensified exploitation has led to legal restrictions since 2010 (Silvetti et al. 2013). This affects forest resource exploitation strategies, especially by subsistence farmers. Obtaining logging permits is made difficult by not having property titles for their land, or by not being able to process their access in the Personal Registry of Owners. In addition, management and travel expenses and access to the information necessary to carry out the administrative procedures are generally out of their reach. Without these logging permits, they cannot sell or trade any forest product (Cabrol and Cáceres 2017). In the case of the cattle ranchers interviewed, their use of the forest aims to sustain the cattle ranching activity itself. Therefore, the NCP priority is not firewood for sale, but rather those NCP linked to the predominant livestock raising. Fruits, leaves, and shade provided by trees and shrubs for the benefit of both cattle and goats, or wood for posts and rods for the maintenance of fences, corrals, and paddocks are some examples. Given the redundancy of good quality firewood traits and attributes within the biological community, it is not justified to burn species that are useful for timber and non-timber NCP, especially if they are not abundant or are restricted to certain areas. Thus, the balance is tilted toward a preference for more abundant or locally accessible species for firewood.

CONCLUSION

Local and scientific perspectives showed a large degree of agreement on the traits and attributes that define good-quality firewood, tested through the WCG. In the case of local actors, the assessment of a species firewood quality was based on their experience in forestry activities and also as users. The ecologists relied on their disciplinary knowledge and experience as firewood users.

The highest fuel values did not strictly correspond to the species most preferred by local actors. This is because, while all social actors agreed that the density of the wood is important in determining its quality, they also agreed that firewood that is overly dense has undesirable outcomes when burned. Furthermore, while the FVI includes some traits and qualities considered desirable, when assessing firewood quality, people also consider other factors that do not intervene in this index. Specifically, there is a differential allocation of resources and a hierarchy among the different NCP in which the studied species are involved, according to a) the experience in the activity, because it provides more information on the performance of the different species that a priori cannot be identified through the traits and attributes recognized as important for firewood quality; b) perceived accessibility and logging and harvesting effort; c) the feasibility of exploiting forest resources within the context of current regulations; d) local abundance of the species; e) particular species demanded by the market, and f) the main productive activity of the actors, which determines priorities among NCP.

In summary, in our study of firewood, the scientific perspective —represented by the quantitative study of the physical properties of the wood and the opinion of the researchers— and the heterogeneous perspectives of local actors roughly agree. However, neither of them fully substitutes for the other. Instead, in determining priorities for the use of different native species for firewood, the incorporation of local actor values and narratives around wood provides a picture that is both richer and more nuanced than one based solely on quantitative physical properties. Our findings illustrate, more generally, the importance of interweaving scientific and local perspectives in the valuation of NCP and decision making on this basis.

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