

Chapter 7

Impact of the Invasive *Prosopis juliflora* on Terrestrial Ecosystems



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Abstract Invasive non-native plants are changing ecosystems and native biodiversity, and modifying soil microbial feedback. The invasive species *Prosopis juliflora* (Sw.) D.C. (mesquite) has been introduced into several ecosystems, especially in tropical and subtropical regions, causing economic, ecological and health problems. This article reviews *P. juliflora* ecophysiological and reproductive attributes, such as phenology, vegetative, seed germination and dispersal, allelopathy and invasion mechanisms. We found that *P. juliflora* invasion has negative impacts on native biodiversity, ecosystem structure and function, bulk soil, seed bank, and hydrological cycle. We discuss *P. juliflora* as a ruminant food and for human use, and new management techniques. The easy naturalization *P. juliflora* in tropical regions has been explained by allelopathy, repeated flowering, vegetative propagation, production and dispersal of huge viable seeds. In particular, *P. juliflora* produces allelochemicals that are not produced in close relatives. Such chemicals have facilitative effects on associated vegetation in the native range, but have detrimental effects in the introduced range. Management strategies are presented to control *P. juliflora* invasion.

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7.1 Introduction

Many human activities, such as agriculture, recreation, global trade and transportation have promoted both the intentional and accidental spread of species across their natural dispersal barriers (Kolar and Lodge 2001). A number of introduced species have been established and spread in the new range and are considered pests for agricultural, landscape and horticultural sector as they pose economic threats to these industries (Barbier et al. 2013). Several authors have considered the increasing number of introduced or invasive species as a major component of global change because of their potential to alter social-ecological systems (Richardson et al. 2011; Moodley et al. 2013; Potgieter et al. 2013; Shackleton et al. 2014). Biological invasions are recognized as one of the most important causes of ecosystem degradation, community structure, local species and biodiversity loss worldwide (Wardle et al 2001; Pyšek et al. 2012).

Prosopis L. is a genus with 44 species of medium-sized trees and shrubs belonging to family Fabaceae, subfamily Mimosoideae (Burkart 1976). Naranjo et al. (1984) and Hunziker et al. (1986) have reported the possibility of interspecific hybridization between *Prosopis juliflora* (Sw.) D.C. (Fabaceae) and *P. pallida* (Humb. & Bonpl. ex Willd.) Kunth, which led to the difficulty in differentiating the two taxa. Despite molecular studies were useful in differentiating the two species (Landeras et al. 2006; Sherry et al. 2011), such morphological similarities led to misidentification of *Prosopis* species and consequently all records of introduction of *Prosopis* need to be reevaluated. To avoid this problem, it is often referred to as the *P. juliflora* – *P. pallida* complex (Pasiiecznik et al. 2001). *Prosopis* was found to occur as a native or introduced species in 129 countries worldwide mainly in the hot arid and semi-arid climatic regions of the world (Shackleton et al. 2014). The numerous goods and services provided by *Prosopis* have led to global introductions and have made some species important for local communities (Pasiiecznik et al. 2001; Shackleton et al. 2014). At least 19 (invasive and weedy) of the 44 species in the genus *Prosopis* are known to generate benefits and costs, with the rest being primarily beneficial in their native ranges (Shackleton et al. 2014). It has been introduced to different parts of the world for different purposes, but it has become aggressive invader in most introduced ranges. For example, it was introduced to Sudan in 1917 to combat desertification and to provide fuelwood (Elfadl and Luukkanen 2006). Similarly, this species was brought to Lake Baringo, Kenya, in the 1980s to alleviate fuelwood shortage (Mwangi and Swallow 2005). *Prosopis juliflora* (Sw.) D.C. was introduced to India during late nineteenth century for the rehabilitation of sodic lands and to supply of fuelwood, fodder, timber, and fiber (Mishra et al. 2003; Sharma and Dakshini 1996) and into Ethiopia in the 1970s and

1980s mainly for soil and water conservation (Tegegn 2008). In fact, *P. juliflora* is present in IUCN's new list of 100 world's worst invasive alien species (Luque et al. 2014).

Management of the invaded species is inefficient in many areas due to lack of knowledge on key aspects of the invasive species. For proper management of *P. juliflora*, it is important to understand the reasons for introductions, benefits, costs, ecology and scales of invasions (Shackleton et al. 2014; Wilson et al. 2014). All of the used approaches for controlling mesquite were mainly to maximize its benefits and minimize its negative impacts (Wise et al. 2012). Patnaik et al. (2017) highlights the dual role of *P. juliflora* and itemizes the facts that make it a blessing in some contexts and a bane in other contexts with a more realistic view. Previous and recent reviews on genus *Prosopis* have focused on the special attributes that give plants competitive advantage, origin and systematics, spread and distribution, impacts, benefits and management (Patnaik et al. 2017 and Shackleton et al. 2014). This review article synthesizes all aspects of the taxonomy, current distribution, history of introduction and spread, ecological constrains (including preferred climate, substratum and habitats), ecophysiological responses to biotic and abiotic factors, biology (including phenology, vegetative and reproductive biology, seed germination and dispersal). Although, we review why *Prosopis juliflora* is invasive in many arid regions, where it was introduced while it is not invasive in its native distribution environment and areas. This will particularly help to find clues of its invasion mechanism (congeneric and biogeographic approach). Indicating potential trade-offs between economic benefits (ruminants feed and human uses) from biomass use and ecological impacts (aboveground, belowground, water and soil fertility) within a defined landscape, whilst also considering interventions in other habitats, will aid decision making, planners and risk managers about its better management in arid and semi-arid regions including Middle East and North Africa in a sustainable way.

7.2 Current Distribution and Status

Most species of the genus *Prosopis* are native to the Americas, ranging from the southwestern USA, through Mexico and Central America into South America, as far as Argentina (Morgan et al. 2017). It was then introduced to Ethiopia, Kenya, Sudan, Eritrea, Iraq, Pakistan, India, Australia, South Africa, the Caribbean, the Atlantic Islands, Venezuela, Bolivia, Brazil, the Dominican Republic, El Salvador, Nicaragua, the United States (USA), and Uruguay (Abdulahi et al. 2017) where *P. juliflora* is an invasive weed. At present, *Prosopis juliflora* are distributed worldwide, they are more frequently invasive in Mediterranean, tropical and arid climates (Fig. 7.1). Furthermore, Table 7.1, demonstrate the Global distribution of *Prosopis* species.



Fig. 7.1 Worldwide distribution of reported *Prosopis juliflora* in different countries

7.2.1 Native Range: Climate, Soil and Habitats

P. juliflora is a shrub native to Mexico, South America and the Caribbean (Burkart 1976; Pasiiecznik et al. 2001). It requires at least 250 mm annual rainfall, but some have been found in areas with <100 mm (Morgan et al. 2017). Kaur et al. (2012) identified Venezuela as one of the native ranges of *P. juliflora*. Detrimental and beneficial mechanisms do not act in isolation from each other in nature. The relative importance of these two processes in a particular plant community determines the structure of that community (Callaway and Walker 1997). Many *Prosopis* species, in their native ranges, contribute with higher concentrations of organic matter, nitrogen, phosphorus and potassium beneath their canopies and behave as strong facilitators of other species (Tiedemann and Klemmedson 1973). In its native range in Venezuela, *P. juliflora* probably has much stronger facilitative effects on neighbours than other leguminous tree species (Larrea-Alcázar and Soriano 2008).

However, in the introduced range, *P. juliflora* has both facilitative and allelopathic effects. However, the allelopathic effects of the litters of *P. juliflora* override its potential positive effects on soil fertility. For example, El-Keblawy and Abdelfatah (2013) assessed the impact of *P. juliflora* on the soil and associated flora in the natural habitats of the United Arab Emirates and concluded that this species has facilitative effects in relation to the available nutrients (i.e., most important macro-nutrients K, N and P were increased). In addition, *P. juliflora* increased the organic matter content, which would also increase the water holding capacity that would improve soil texture and increase soil moisture. However, the negative effect of *P. juliflora*

Table 7.1 Global distribution of *Prosopis* species

Country	<i>Prosopis</i> species status	References
Afghanistan	<i>P. cineraria</i> (NA); <i>P. farcta</i> (W) <i>P. juliflora</i> (N)	Sohrabi et al. (2011) and GBIF (2013)
Algeria	<i>P. farcta</i> (NA), <i>P. juliflora</i> (I)	Habit et al. (1990), Pasiecznik et al. (2001), and ISSG (2005)
Angola	<i>Prosopis</i> spp. (N)	Poynton (2009)
Antigua and Barbuda	<i>P. juliflora</i> (N)	Johnston (1962)
Argentina*	<i>P. abbreviata</i> (NA), <i>P. affinis</i> (W), <i>P. alba</i> (NA), <i>P. algarobilla</i> (NA), <i>P. alpataco</i> (NA), <i>P. argentina</i> (NA) <i>P. caldenia</i> (W), <i>P. calingastana</i> (NA), <i>P. camperstris</i> (W), <i>P. castellanosii</i> (NA), <i>P. chilensis</i> (NA), <i>P. denudans</i> (NA), <i>P. elata</i> (NA), <i>P. ferox</i> (NA), <i>P. fiebrigii</i> (NA), <i>P. flexuosa</i> (NA), <i>P. glandulosa</i> (N), <i>P. hasslei</i> (W), <i>P. humilis</i> (W), <i>P. juliflora</i> (N), <i>P. kuntzei</i> (W), <i>P. laevigata</i> (NA), <i>P. nigra</i> (W), <i>P. pugionata</i> (NA), <i>P. reptans</i> (NA), <i>P. rojasiana</i> (NA), <i>P. ruizleali</i> (NA), <i>P. ruscifolia</i> (W), <i>P. sericantha</i> (NA), <i>P. strombulifera</i> (NA), <i>P. torquata</i> (NA), <i>P. tamarugo</i> (N), <i>P. vinalilla</i> (NA), <i>P. hybrids</i> (I/W)	CABI (2005) and GBIF (2013)
Aruba	<i>P. juliflora</i> (N)	D.C.B (2009)
Ascension Island*	<i>P. juliflora</i> (I)	Pickup (1999) and Belton (2008);
Australia*	<i>P. glandulosa</i> (I), <i>P. juliflora</i> (I), <i>P. pallida</i> (I), <i>P. velutina</i> (I), <i>P. hybrids</i> (I)	Panetta and Carstairs (1989), Osmond (2003), and van Klinken et al. (2006)
Azerbaijan	<i>P. farcta</i> (NA)	CABI (2005)
Bahamas	<i>P. juliflora</i> (N)	CABI (2005)
Bahrain	<i>P. farcta</i> (NA), <i>P. glandulosa</i> (U), <i>P. juliflora</i> (N)	Pasiecznik et al. (2001) and AFTD (2009)
Bangladesh	<i>P. juliflora</i> (N)	CABI (2005)
Barbados	<i>P. juliflora</i> (N)	Jonston (1962)
Belize	<i>P. juliflora</i> (NA)	AFTD (2009)
Benin	<i>P. africana</i> (NA) <i>P. juliflora</i> (U)	AFTD (2009) and CABI (2009)
Bermuda	<i>P. juliflora</i> (U)	CABI (2009)
Bolivia	<i>P. alba</i> (NA), <i>P. algarobilla</i> (NA), <i>P. alpataco</i> (NA), <i>P. chilensis</i> (NA), <i>P. denudans</i> (NA), <i>P. elata</i> (NA), <i>P. ferox</i> (NA), <i>P. flexuosa</i> (NA), <i>P. juliflora</i> (NA), <i>P. kuntzei</i> (NA), <i>P. laevigata</i> (NA), <i>P. nigra</i> (NA), <i>P. pallida</i> (NA), <i>P. ruscifolia</i> (NA), <i>P. vinalillo</i> (NA)	Pasiecznik et al. (2001), Grandtner (2005), and AFTD (2009)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Botswana	<i>P. chilensis</i> (I), <i>P. glandulosa</i> (I), <i>P. pallida</i> (N), <i>P. juliflora</i> (N), <i>P. velutina</i> (I), <i>P. hybrids</i> (I)	Botswana Gov (2009), Poynton (2009), and Muzila et al. (2011)
Brazil	<i>P. affinis</i> (N/W), <i>P. alba</i> (N), <i>P. flexuosa</i> (NA), <i>P. juliflora</i> (I), <i>P. laevigata</i> (NA), <i>P. pallida</i> (N), <i>P. rubriflora</i> (NA), <i>P. ruscifolia</i> (N)	Pasiecznik et al. (2001), Leão et al. (2011), and de Olivera et al. (2012)
Brunei Darussalam	<i>P. juliflora</i> (U)	Pasiecznik et al. (2001) and AFTD (2009)
Burkina Faso	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Ræbild et al. (2003), Weber et al. (2008)
Cambodia	<i>P. juliflora</i> (U)	AFTD (2009)
Cameroon	<i>P. africana</i> (NA)	Pasiecznik et al (2001) and AFTD (2009)
Cape Verde	<i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. pallida</i> (I) <i>P. velutina</i> (N), <i>P. hybrids</i> (I)	FAO (2006), AFTD (2009), and Cienfiala et al. (2013)
Cayman Islands	<i>P. juliflora</i> (N)	CABI (2005)
Central African Republic	<i>P. africana</i> (NA)	AFTD (2009)
Chad	<i>P. africana</i> (NA), <i>chilensis</i> (N), <i>P. juliflora</i> (I)	Pasiecznik et al. (2001), ISSG (2005), Geesing et al. (2004)
Chile	<i>P. alba</i> (NA), <i>P. alpataco</i> (NA), <i>P. burkartii</i> (NA), <i>P. chilensis</i> (W), <i>P. flexuosa</i> (NA), <i>P. fruticosa</i> (NA), <i>P. laevigata</i> (NA), <i>P. strombulifera</i> (NA), <i>P. tamarugo</i> (W)	Pasiecznik et al. (2001), AFTD (2009), and GBIF (2013)
Colombia	<i>P. flexuosa</i> (NA), <i>P. juliflora</i> (W), <i>P. nigra</i> (W), <i>P. pallida</i> (NA)	Grandtner (2005), Vallejo et al. (2012), and GBIF (2013)
Costa Rica	<i>P. juliflora</i> (NA)	Burkart (1976)
Cote d'Ivoire	<i>P. africana</i> (NA), <i>P. juliflora</i> (U)	CABI (2005)
Cuba	<i>P. juliflora</i> (N), <i>P. glandulosa</i> (N)	Johnston (1962), Pasiecznik et al. (2001)
Curacao	<i>P. juliflora</i> (N)	Pasiecznik et al. (2001)
Cyprus	<i>P. farcta</i> (NA)	Pasiecznik et al. (2004)
Djibouti*	<i>P. cineraria</i> (I), <i>P. juliflora</i> (I), <i>P. pallida</i> (I),	Pasiecznik et al. (2001)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Dominican Republic	<i>P. juliflora</i> (N)	ISSG (2010), and Pasiecznik et al. (2001)
Ecuador	<i>P. chilensis</i> (NA), <i>P. juliflora</i> (NA), <i>P. pallida</i> (NA)	Grandtner, (2005), GBIF (2013)
Egypt*	<i>P. africana</i> (NA), <i>P. chilensis</i> (N), <i>P. farcta</i> (NA), <i>P. glandulosa</i> (I), <i>P. juliflora</i> (I), <i>P. velutina</i> (I)	Pasiecznik et al. (2001), Ghazali (2006), Weber et al. (2008)
El Salvador	<i>P. juliflora</i> (NA)	Burkart (1976)
Eritrea*	<i>P. juliflora</i> (I)	Zimmerman (1991) ISSG (2005), Bokerezion (2008)
Ethiopia*	<i>P. africana</i> (NA), <i>P. chilensis</i> (I), <i>P. juliflora</i> (I), <i>P. pallida</i> (I)	ISSG (2005), Berhanu and Tesfay (2006), Shiferaw et al. (2004), FARM-Africa (2008)
Fiji	<i>P. pallida</i> (U)	Gallaber and Merlin (2010)
Galapagos	<i>P. juliflora</i> (NA), <i>Prosopis</i> spp. (NA)	Wiggins et al. (1971)
Gambia	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Pasiecznik et al. (2001)
Georgia	<i>P. farcta</i> (W)	Pasiecznik et al. (2001)
Ghana	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Pasiecznik et al. (2001)
Guam	<i>P. pallida</i> (N)	Fosberg et al. (2013)
Guatemala	<i>P. juliflora</i> (NA)	Pasiecznik et al. (2001)
Guinea	<i>P. africana</i> (NA)	Pasiecznik et al. 2001
Guinea-Bissau	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	AFTD (2009)
Haiti	<i>P. chilensis</i> (U), <i>P. flexuosa</i> (IP), <i>P. juliflora</i> (I), <i>P. velutina</i> (N)	Burkart (1976), Lee et al. (1992), and Timyan (1996)
Hawaii*	<i>P. juliflora</i> (I), <i>P. pallida</i> (I), <i>P. hybrids</i> (I)	Kaur et al. (2012)
Honduras	<i>P. juliflora</i> (NA)	Burkart (1976)
India*	<i>P. cineraria</i> (W), <i>P. farcta</i> (NA), <i>P. glandulosa</i> (I), <i>P. juliflora</i> (I), <i>P. pallida</i> (N), <i>P. velutina</i> (N), <i>P. hybrids</i> (I)	Pasiecznik et al. (2004), CABI (2005), FAO (2006), AFTD (2009), Kaur et al. (2012);
Indonesia	<i>P. juliflora</i> (U)	Pasiecznik et al. (2001), CABI (2005)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Iran*	<i>P. cineraria</i> (W), <i>P. farcta</i> (W), <i>P. juliflora</i> (I), <i>P. koelziana</i> (NA)	Pasiecznik et al. (2001), AFTD (2009), Sohribi et al. (2011), Sajad and Sefidi (2012)
Iraq	<i>P. farcta</i> (W), <i>P. juliflora</i> (I)	Burkart (1976), Berhanu and Tesfay (2006)
Israel	<i>P. farcta</i> (W), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Pasiecznik et al. (2001), CABI (2005)
Jamaica	<i>P. juliflora</i> (N)	Pasiecznik et al. (2001)
Jordan*	<i>P. farcta</i> (W), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Pasiecznik et al. (2001), and Quasem (2007)
Kenya*	<i>P. africana</i> (NA), <i>P. chilensis</i> (I), <i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Choge et al. (2002); Mwangi and Swallow (2005), FAO (2006), and Maturi (2013)
Kiribati	<i>P. pallida</i> (U)	Fosberg et al. (1976), GISD (2013)
Kuwait	<i>P. glandulosa</i> (N), <i>P. juliflora</i> (I)	Burkart (1976)
Laos	<i>P. juliflora</i> (N)	AFTD (2009)
Lesotho	<i>Prosopis</i> spp. (N)	Poynton (2009)
Liberia	<i>P. africana</i> (NA), <i>P. juliflora</i> (N)	CABI (2005)
Libya	<i>P. farcta</i> (NA), <i>P. juliflora</i> (I)	CABI (2005)
Madagascar	<i>P. juliflora</i> (N)	Du Puy (1990), CABI (2005)
Malaysia	<i>P. juliflora</i> (U)	CABI (2005)
Malawi	<i>P. glandulosa</i> (I)	Chikuni et al. (2004)
Mali	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Weber et al. (2008), Djoudi et al. (2011)
Mauritania	<i>P. chilensis</i> (U), <i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Gritzner (1979), Jensen and Hajej (2001)
Mariana Islands	<i>P. pallida</i> (N)	Fosberg et al. (1976)
Marquesas Islands	<i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Gallaber and Merlin (2010), and Lorence and Wagner (2013)
Mauritius	<i>P. pallida</i> (N)	Gallaber and Merlin (2010)
Mexico	<i>P. articulata</i> (NA), <i>P. glandulosa</i> (W), <i>P. juliflora</i> (NA), <i>P. laevigata</i> (NA), <i>P. nigra</i> (N), <i>P. palmeri</i> (NA), <i>P. pubescens</i> (NA), <i>P. reptans</i> (NA), <i>P. tamaulipana</i> (NA), <i>P. velutina</i> (W), <i>P. hybrids</i> (I/W)	Grandtner (2005) and GBIF (2013)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Montserrat	<i>P. juliflora</i> (N)	Gallaber and Merlin (2010)
Morocco	<i>P. juliflora</i> (N)	Benata et al. (2008)
Mozambique	<i>P. juliflora</i> (I)	Witt (2013, personal communication)
Myanmar	<i>P. glandulosa</i> (N)	Gallaber and Merlin (2010)
Namibia*	<i>P. chilensis</i> (N), <i>P. glandulosa</i> (I), <i>P. pallida</i> (I), <i>P. juliflora</i> (I), <i>P. velutina</i> (I), <i>P. hybrids</i> (I)	Zimmerman (1991), Smit (2004), and Poynton (2009)
Netherlands Antilles	<i>P. juliflora</i> (N)	Grandtner (2005)
New Caledonia	<i>P. pallida</i> (U)	MacKee (1994)
Nicaragua	<i>P. juliflora</i> (NA)	AFTD (2009)
Niger*	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Geesing et al. (2004), FAO (2006), Weber et al. (2008), and GBIF (2013)
Nigeria	<i>P. africana</i> (NA), <i>P. juliflora</i> (I)	Burkart (1976), Borokini and Babalola (2012)
Oman*	<i>P. cineraria</i> (NA), <i>P. juliflora</i> (I),	Ghazanfar (1996), Al Rawahy et al. 2003 and Al Abri et al. (2004)
Pakistan*	<i>P. cineraria</i> (W), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. koelziana</i> (NA)	Pasiecznik et al. (2004), AFTD (2009), Hussain et al. (2010), Khan et al., (2011)
Panama	<i>P. juliflora</i> (NA)	AFTD (2009)
Papua New Guinea	<i>P. pallida</i> (N), <i>P. juliflora</i> (I)	CABI (2005), and AFTD (2009)
Paraguay	<i>P. affinis</i> (NA), <i>P. algarobilla</i> (NA), <i>P. argentina</i> (NA), <i>P. alba</i> (NA), <i>P. campestris</i> (W), <i>P. chilensis</i> (NA), <i>P. elata</i> (NA), <i>P. fiebrigii</i> (NA), <i>P. hassleri</i> (NA), <i>P. humilis</i> (NA), <i>P. kuntzei</i> (NA), <i>P. juliflora</i> (NA), <i>P. nigra</i> (NA), <i>P. P. rojasiana</i> (NA), <i>P. ruscifolia</i> (W), <i>P. rubriflora</i> (NA), <i>P. sericantha</i> (NA), <i>P. vinalillo</i> (NA)	GBIF (2013)
Peru	<i>P. alba</i> (NA), <i>P. chilensis</i> (NA), <i>P. juliflora</i> (NA), <i>P. laevigata</i> (NA), <i>P. pallida</i> (NA), <i>P. reptans</i> (NA)	Grandtner (2005), GBIF (2013)
Philippines	<i>P. juliflora</i> (N)	Burkart (1976), Gallaber and Merlin (2010)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Polynesia	<i>P. pallida</i> (N)	Burkart (1976), ISSU (2005), Lorence and Wagner (2013)
Puerto Rico	<i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. pallida</i> (N)	Little and Wadsworth (1964), GBIF (2013)
Qatar	<i>P. cineraria</i> (NA), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (N)	Pasiecznik et al. (2001)
Reunion	<i>P. glandulosa</i> (N), <i>P. juliflora</i> (I)	Kueffer and Lavergne (2004), CABI (2005)
Saint Helena	<i>P. juliflora</i> (N)	GISD (2013)
Saudi Arabia*	<i>P. africana</i> (U), <i>P. cineraria</i> (NA), <i>P. farcta</i> (W), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. koelziana</i> (NA)	Pasiecznik et al. (2001) and Hall et al. (2010)
Senegal	<i>P. africana</i> (NA), <i>P. alba</i> (N), <i>P. cineraria</i> (N), <i>P. pallida</i> (N) <i>P. juliflora</i> (I)	Diagne (1992) and Pasiecznik et al. (2001)
Sierra Leone	<i>P. africana</i> (NA), <i>P. chilensis</i> (N)	CABI (2005) and GBIF (2013)
Society Islands	<i>P. juliflora</i> (U), <i>P. pallida</i> (U)	Fosberg (1997)
Somalia	<i>P. chilensis</i> (I), <i>P. juliflora</i> (I)	Zollner (1986) and CABI (2005)
South Africa*	<i>P. alba</i> (I), <i>P. chilensis</i> (I), <i>P. glandulosa</i> (I), <i>P. juliflora</i> (I), <i>P. laevigata</i> (I), <i>P. pubescens</i> (N), <i>P. velutina</i> (I), <i>P. hybrids</i> (I)	Zimmermann (1991), Poynton (2009), Van den Berg (2010), Mazibuko (2012), and Wise et al. (2012)
Spain	<i>P. chilensis</i> (N), <i>P. velutina</i> (N)	Tilstone et al. (1998), Pasiecznik and Peñalvo López (in review)
Sri Lanka	<i>P. cineraria</i> (N), <i>P. juliflora</i> (I)	Parera and Pasiecznik (2005), AFTD (2009)
St Lucia	<i>P. juliflora</i> (N)	AFTD (2009)
St Vincent	<i>P. juliflora</i> (N)	AFTD (2009)
Sudan*	<i>P. africana</i> (NA), <i>P. chilensis</i> (I), <i>P. glandulosa</i> (I), <i>P. pallida</i> (N), <i>P. juliflora</i> (I), <i>P. velutina</i> (I)	Burkart (1976), El Fadl (1997), CABI (2005), FAO (2006), ISSG (2006), and Bokreziou (2008)
Syria	<i>P. farcta</i> (W)	ISSU (2005)
Tajikistan	<i>P. farcta</i> (NA)	GBIF (2013)
Tanzania*	<i>P. africana</i> (NA), <i>P. chilensis</i> (N), <i>P. juliflora</i> (I)	AFTD (2009) and Witt (2013, personal communication)
Thailand	<i>P. juliflora</i> (U)	Pasiecznik et al. (2001)

(continued)

Table 7.1 (continued)

Country	<i>Prosopis</i> species status	References
Togo	<i>P. africana</i> (NA), <i>P. chilensis</i> (N)	AFTD (2009)
Trinidad and Tobago	<i>P. juliflora</i> (N)	ISSG (2013)
Tunisia	<i>P. chilensis</i> (N), <i>P. cineraria</i> (N), <i>P. farcta</i> (NA), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. laevigata</i> (N), <i>P. velutina</i> (N)	Habit and Saavedra (1990)
Turkey	<i>P. farcta</i> (W)	Pasiecznik et al. (2001); ISSU (2005)
Turkmenistan	<i>P. farcta</i> (NA)	GBIF (2013)
Uganda	<i>P. africana</i> (NA), <i>P. juliflora</i> (N)	Pasiecznik et al. (2001)
Ukraine	<i>P. farcta</i> (W)	Pasiecznik et al. (2001)
United Arab Emirates*	<i>P. cineraria</i> (N), <i>P. farcta</i> (NA), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I)	El-Keblawy and Al-Rawai (2007) and AFTD (2009)
United States*	<i>P. alba</i> (N), <i>P. articulata</i> (NA), <i>P. chilensis</i> (W), <i>P. cineraria</i> (N), <i>P. cinerascens</i> (NA), <i>P. farcta</i> (I), <i>P. glandulosa</i> (W), <i>P. juliflora</i> (I), <i>P. laevigata</i> (NA), <i>P. pallida</i> (I), <i>P. pubescens</i> (W), <i>P. strombulifera</i> (W), <i>P. velutina</i> (W), <i>P. hybrids</i> (I/W)	Johnston (1962), Grandtner (2005), and GBIF (2013)
Uruguay	<i>P. affinis</i> (NA), <i>P. alba</i> (NA), <i>P. caldenia</i> (W), <i>P. chilensis</i> (NA), <i>P. nigra</i> (NA), <i>P. ruscifolia</i> (NA)	GBIF (2013)
Venezuela	<i>P. flexuosa</i> (NA), <i>P. juliflora</i> (W)	Grandtner (2005) and Burkart (1976)
Vietnam	<i>P. juliflora</i> (N)	Pasiecznik et al. (2001)
Virgin Islands	<i>P. juliflora</i> (N), <i>P. pallida</i> (N)	Little and Wadsworth (1964) and Burkart (1976)
Western Sahara	<i>P. juliflora</i> (N)	Habit et al. (1990) and Witt (2013, personal communication)
Yemen*	<i>P. chilensis</i> (I), <i>P. cineraria</i> (NA), <i>P. farcta</i> (NA), <i>P. glandulosa</i> (N), <i>P. juliflora</i> (I), <i>P. koelziana</i> (NA)	FAO (2006) and Geesing et al. (2004)
Zanzibar	<i>P. juliflora</i> (N)	Nahonyo et al. (2005)
Zimbabwe	<i>P. juliflora</i> (N), <i>P. pallida</i> (U)	White (1962) and Poynton (2009)

Status codes (*sensu* Pyšek et al. 2004 with additional category weedy to describe native species that are invasive in their native ranges) are given in brackets: *N* naturalised, *I* invasive, *NA* native, *W* weedy, *U* unknown. Countries partaking in management of *Prosopis* species are marked with an asterisk

on the associated flora indicates that the allelopathic effects of the litters may override its potential positive effects on soil fertility (El-Keblawy and Abdelfatah 2013). In India, Kaur et al. (2012) showed that *P. juliflora* form resource islands by accumulating total organic N and organic carbon in their rhizosphere soil. However, the allelochemicals produced by this species outweigh the facilitative by nutrient enrichment (Kaur et al. 2012).

The history and range of distribution of the invasive *P. juliflora* – *P. pallida* complex has been covered by several authors including Burkart (1976), Habit and Saavedra (1990a, b, c), Poynton (1990), Felker and Moss (1996) and Perry (1998). In their monograph about *P. juliflora*, Pasiecznik et al. (2001) described the environmental conditions where this complex grows and creates environmental problems. According to Pasiecznik et al. (2001), the *P. juliflora* – *P. pallida* complex has been recorded in most of the African countries.

7.2.2 *Introduced Range: Climate, Soil and Habitats*

In the introduced range *P. juliflora* can grow in a wide range of conditions ranging from sand dunes to clay soils; from saline to alkaline soils; from areas below 200 to more than 1500 m above sea level; and from 50 to 1500 mm mean annual rain fall (Pasiecznik et al. 2004; Zeila et al. 2004). It can also withstand and survive temperatures from as high as 50 °C (air temperature) and 70 °C (soil temperature) (Pasiecznik et al. 2004). The introduction of *Prosopis* species from the Americas started to Senegal in 1822, and then to Australia, Hawaii, India, Philippines, South Africa, Sri Lanka and Sudan in the late 1800s and early 1900s (Pasiecznik et al. 2001). However, reforestation programmes after major droughts in the Sahel encouraged the widespread introductions into Africa and Asia between the 1970s and 1990s (Shackleton et al. 2014). The reasons of the introductions of *Prosopis* include providing fodder, fuelwood and shade in the arid areas of South Africa and Australia. In addition, the introductions were for dune stabilization, afforestation and fuel wood supply, provision of and fodder in several African countries. In India and Middle Eastern countries, the introductions were for rehabilitating degraded soil, local greening, ornamental cultivation and soil stabilization (Shackleton et al. 2014).

Prosopis juliflora is a major invasive species in India, and has also invaded other regions throughout the world including Saharan and southern Africa, the Middle East, Pakistan, and Hawaii (USA) (Pasiecznik et al. 2001), where it appears to strongly suppress the species native to those regions (Kaur et al. 2012). *Prosopis juliflora* forms pure stands in its invaded range in India and Arabia (Figs. 7.1 and 7.2), and occurs in forests, wastelands and at the boundaries of crop fields. *P. juliflora* also occurs in saline habitats in Hawaii USA. Above all, the worst thing is its negative impacts on the ecosystem like forming impenetrable shrubby thickets, invading water courses, lowering the water-table and thus indirectly starving plants of other species of moisture and nutrients, creating what are known as ‘green deserts’, largely devoid of life, instead of meeting the stated objective (Abdulahi et al.

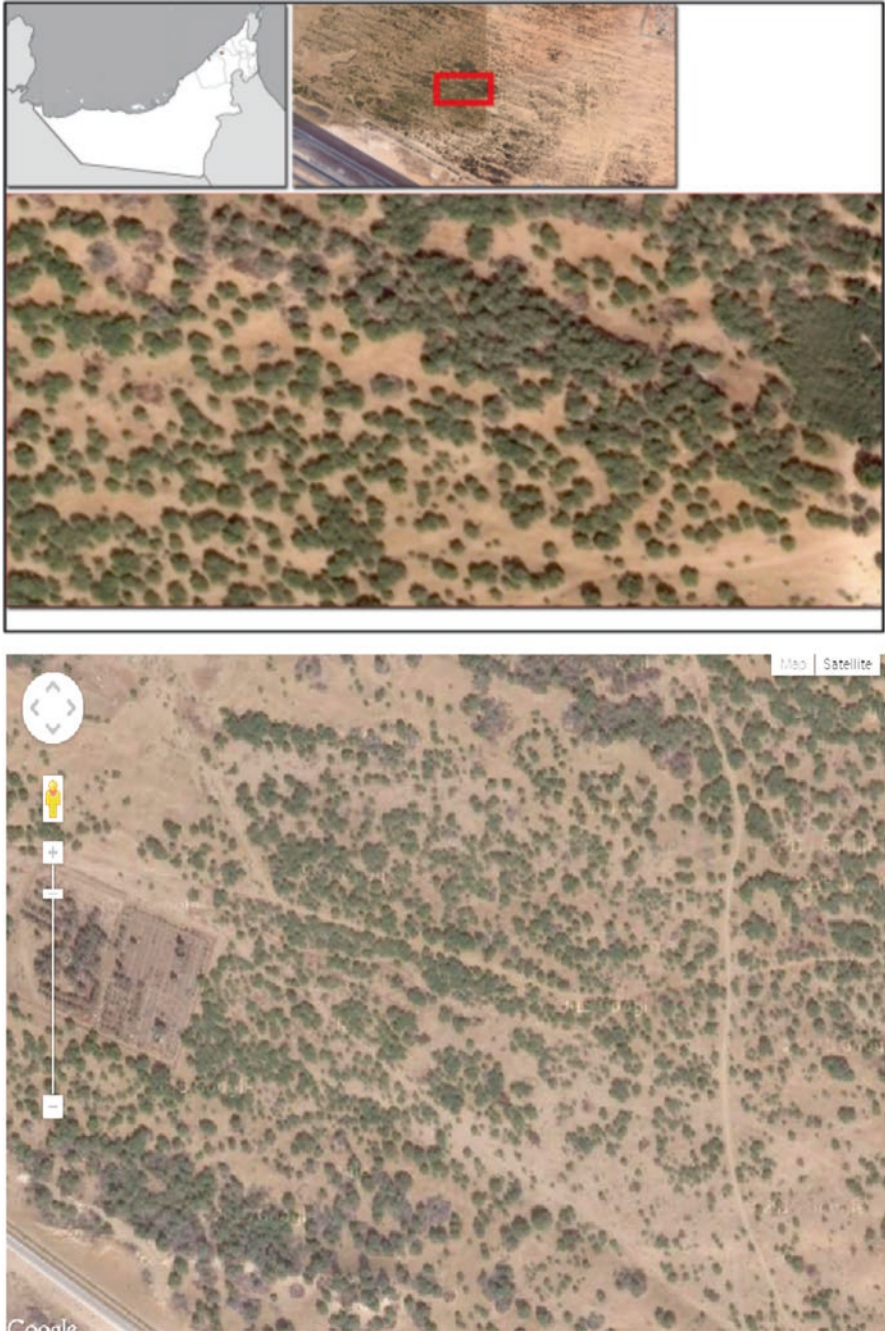


Fig. 7.2 Satellite images show the invasion of *P. juliflora* to sand dunes next to Sharjah Airport, United Arab Emirates. Before the invasion of *P. juliflora*, these sandy dunes were almost barren of vegetation

2017). Even in the arid lands of the Arabia, *P. juliflora* dominates areas with shallower water table (El-Keblawy et al. 2015). These functional properties of *Prosopis* and other foster its adaptability and support the invasion of the species across various agro-ecosystems including wetlands, dry lands, and irrigated agricultural lands (Shiferaw et al. 2004).

The *P. juliflora* have typically invaded areas in Arabian Peninsula where water table is close to the ground, such as gravel deserts, open plains, sand sheets, wadis and edges of farms (El-Keblawy and Al-Rawai 2007; El-Keblawy and Abdelfatah 2013; El-Keblawy et al. 2015; Thomas et al. 2016). In Saudi Arabia, *P. juliflora* was reported as a ruderal plant, mostly found inside the urban and suburban areas and has rarely been seen among the native plant populations (Thomas et al. 2016). In the UAE, this species was reported in many natural habitats that have shallower water table. In addition, several farms of Ras Al Khaimah have been invaded and, consequently, ruined during the last 30 years (Ali El-Keblawy, unpublished data). *Prosopis juliflora* was identified as the most prominent invasive species in majority of lowlands of Saudi Arabia (Thomas et al. 2016).

This species was found as a troublesome exotic in the main inhabited island (Farasan Al-Kabir) in the Red Sea; approximately 12.5% of the total cover of inland vegetation is represented by *P. juliflora*. In addition, this species was found to be the most troublesome one in Najd, Central region of Saudi Arabia, which is considered as the most arid part of country; average annual rainfall is less than 100 mm. In this region, *P. juliflora* was reported as a ruderal plant, mostly found inside the urban and suburban areas and rarely seen among the native plant populations (Thomas et al. 2016). Careful examination of the *P. juliflora* plants showed the presence of *P. juliflora* growing mixed with *P. pallida* in most of the invaded habitat of the UAE and this complex is highly aggressive and coppices so well that it crowds out native vegetation (El-Keblawy and Al-Rawai 2007). The suitable habitat of *P. juliflora* is roadsides, but it is also planted in close spacing at an area of few hectares on sandy desert. Similarly, this species has been introduced to Qatar during 1950s and it grows around farmland as well as in depressions (Ahmad and Ismail 1996).

7.2.3 History of Introduction and Spread

Prosopis juliflora (Sw.) D.C. is native to south-west United States and north-west Mexico, and it is invasive in many tropical and subtropical regions, including North Africa and the Arab Gulf region (Abbas et al. 2016). *P. juliflora* was introduced to the UAE in the 1970s for greening deserts (El-Keblawy and Al-Rawai 2007; Tourenq and Shuriqi 2010). During the last four decades, this species has escaped the forests and currently is considered as a serious weed (Figs. 7.1 and 7.2). In Bahrain, scattered patches of young *P. juliflora* plants were recorded on coastal lowland. The presence of a huge single isolated *P. juliflora* tree in the central plateau of Bahrain indicates the probability of its early introduction. In Ethiopia, *Prosopis* was introduced in the late 1970's, or early 1980's through collaborative efforts of

governments and international development organizations to rehabilitate degraded soils, to supply firewood and fodder and to combat desertification (Berhanu and Tesfaye 2006; Rettberg and Müller-mahn 2012; Shackleton et al. 2014). Now a day, around one million hectares of Ethiopia are already covered by *Prosopis* (Abdulahi et al. 2017). In Egypt, *P. juliflora* was introduced intentionally in the Gebel-Elba National Park by local people of Old-Hala'ib. village for agroforestry purposes during 1980s. However, they found it as highly invasive, spreading rapidly, destroying the local flora (Abbas et al. 2016). At the moment, now, it has been spread to 116 Km Northwest of its introduced range in the wadis of Shalal, Mericowan, Sarara, Shab and Aibib (Shiferaw et al. 2004; Hundessa 2016).

In the arid and semi-arid areas of Kenya, the *Prosopis* species were first introduced to rehabilitate quarries near the coastal town of Mombasa with seed sourced from Brazil and Hawaii in the early 1970's as a source of fuelwood and later, in the rehabilitation of degraded lands (Oduor and Githiomi 2013). In the Sudan, *Prosopis* spp. were introduced in many semi-arid areas, to combat desertification and provide fuel wood and fodder (Elfadl 1997a, b). However, this species have spread rapidly into fertile, productive areas, and irrigation and drainage channels (Morgan et al. 2017) (Fig. 7.3).

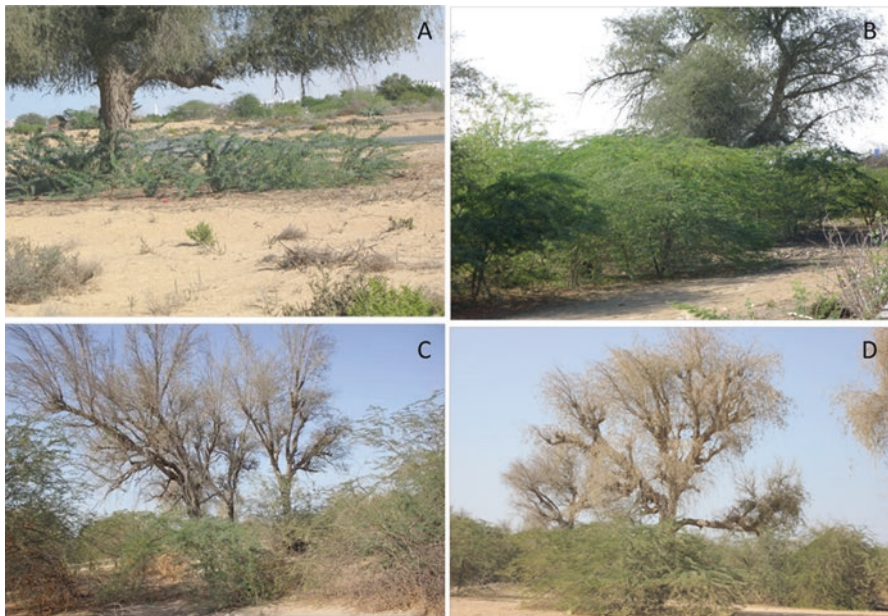


Fig. 7.3 *Prosopis juliflora* and its congeneric species *Prosopis cineraria* are co-occurring in many habitats of the United Arab Emirates. A. *Prosopis cineraria* provided the shade for domestic and wild animals that left big amount of *Prosopis juliflora* seeds resulted in dense growing of their seedlings under the crown of native *Prosopis cineraria* (b) the dense competition between the two congeneric species, especially for water resources (c and d) the intense competition between the two species resulted in death of the native *Prosopis cineraria*

The highly invasive nature of *P. juliflora* is a result of several factors; it is extremely drought resistant, a quality mainly attributed to its deep taproot (Samuel et al. 2013). Rivers and water canals also play a significant role in the dissemination of seeds to different areas. Swamps, roadsides and irrigation canals are highly invaded by *Prosopis*. This shows *Prosopis* establishes well in areas where water is available and also where surface runoff water is present for its seed dispersal. In Kenya, the banks of the Tana river, which is the largest river in Kenya, have been invaded by *Prosopis*. Seeds could be dispersed by water, but the main dispersal agent is the digestive system of most herbivores (Maundu et al. 2009).

7.3 Ecological Constraints

In the native range *Prosopis juliflora* exhibits different physiological responses to environmental variables, mainly temperature, rainfall and day length (Pasicznik et al. 2001). *P. juliflora* can grow in arid and semi-arid regions because of its resistance to drought and heat. It thrives on all soil types under variable climatic conditions (Sawal 2004).

7.3.1 Climate

Prosopis juliflora is reported to tolerate an annual precipitation of 150 to 1670 mm, annual temperature of 20.3 °C to 28.5 °C, and pH around neutral (Ruskin 1980 and Larrea-Alcázar and Soriano 2008) but it can grow in areas with annual rainfall less than 100 mm as in the Central region of Saudi Arabia (Thomas et al. 2016) and UAE (El-Keblawy and Abdelfatah 2013). Given the fact that *P. juliflora* is evergreen and has fast growth all over the year, this supports the hypothesis that it relies mainly on underground water as the main source for life. *P. juliflora* is frost sensitive (Felker et al. 1982) and severe frost can cause stem and tree mortality in countries with cold weather. Consequently, there is doubt about the presence of this species in the Mediterranean climates of countries such as Morocco, Algeria, Tunisia, Libya and Egypt. For example, winter frosts occur over much of Egypt making it unsuitable for the *P. juliflora* – *P. pallida* complex unless it grows in sheltered or coastal locations (Burkart 1976). Similarly, Akrimi (1990) stated that cold sensitive *P. juliflora* was killed outright in Tunisia. Most of *Prosopis* species that are present in these countries are more likely to be *P. glandulosa* Torr., *P. velutina* Wooton, *P. chilensis* (Molina) Stuntz or hybrid forms from these species (Burkart 1976). In northern India, *P. juliflora* grows in regions that have high temperatures and high light intensities for most of the year. However, during the winter (December–January), the nocturnal temperatures fall to 2 °C, while during the summer (May–June), the temperatures of the day often exceed 45 °C (Shirke and Pathre 2004). *P. juliflora* shows a high capacity to adapt to these extreme temperatures, especially, to the high

temperatures in summer. Similarly, in the UAE, where temperatures in summer can reach around 50 °C, *P. juliflora* grows nicely all over the year (El-Keblawy et al. 2015).

7.3.2 *Substratum*

Prosopis juliflora is a facultative phreatophyte that has a higher tolerance to droughts and ability to access declining groundwater tables through its deeper root system. It survives and flourishes in heavy or sandy soils, as well as saline dry flats and it can tolerate grazing (Morgan et al. 2017). In the Lagunillas semiarid enclave in the Venezuelan Andes *P. Juliflora* is present on loamy clay soils with high concentrations of organic matter (4–5%), nitrogen (0.15–0.30%), potassium (0.4–1.1 ppm), magnesium (2.0–5.5 me/l) and calcium (30–45 me/l) (Larrea-Alcázar and Soriano 2008). *Prosopis juliflora* usually grows in non-saline soils in most of its native and introduced range, but it has been recorded to occur in saline habitats in Hawaii USA and Gujarat, India (Kaur et al. 2012). In the UAE, it is reported in both saline and non-saline habitats as well as farms and disturbed sites (El-Keblawy and Al-Rawai 2007).

7.4 New Insights into Traits That Promote Invasion

7.4.1 *Morphological Characteristics*

The life history traits of invasive plants demonstrate an important feature that can help themselves in the invasion, adaptation and establishment in a new habitat or introduced ones. The morphological and agro-physiological characteristics include plant height, dispersal efficiency, competition potential and sprouting capacity (Gibson et al. 2011). However, the human and environmental factors are also an important contributor in the invasion and dispersal of exotic plant species into a new habitat (Castro-Díez et al. 2011). *Prosopis juliflora* (mesquite, vilayati babul, algarrobo) is a xerophytic evergreen and fast growing tree, native to frost-free tropical regions of Peru, Central America and the Caribbean, with long lateral shallow and deep taproot systems that are also able to fix nitrogen (Burkart 1976; Pasicznik et al. 2001). Stem is green-brown, sinuous and twisted, up to 5–10 m in height, with strong axial thorns situated on both sides of the nodes, the bark is rough and light red in colour. Leaves are compound, bipinnate with one or sometimes two pairs of rachis, each having 12 to 25 pairs of green folioles (Silva 1986). Flowers are small (4–6 mm long, 1 cm long), produced in inflorescences of various sizes and shapes but generally in spike-like inflorescences (racemes) 9.5–16.5 cm long (Díaz 1995). *Prosopis* flowers are arranged in cylindrical racemes of about 300–400 flowers

(Zaitoun et al. 2009), in clusters of 2–5, at the end of the branches. Flowers are hermaphrodite, sometimes sterile, actinomorphic and pentamerous (Burkart 1976). Fruit is a non-dehiscent pod, curved and about 4 mm thick, 1 cm wide and up to 15 cm in length made up of light yellow hardened epicarp, fleshy mesocarp and woody endocarp which contains seed (Silva 1986).

7.4.2 Reproductive Features

7.4.2.1 Phenology and Vegetative Growth Attributes

Prosopis trees generally initiate flowering and fruiting in the third or fourth year after germination. First flowering is dependent on optimal conditions and under drought conditions or very poor soils it can be considerable later (Pasicznik et al. 2001). *Prosopis* species produce flowers every year increasing gradually up to 10–20 years and may be expected to continue at this high level for several decades. In the native range *P. juliflora* exhibits different physiological responses to environmental variables, mainly temperature, rainfall and day length (Pasicznik et al. 2001), so variation in the onset of flowering is present between different populations due to climatic variation. Flowering is also variable within and between trees of the same population. Despite, flowering times are genetically controlled (Graham 1960; Pasicznik et al. 2001). *P. juliflora* flowering season at the native range varies, with one or two periods of main flower production. It generally coincides with the wet season, from December to February and it is delayed from March to April and from July to September when there are two periods of flowering. Therefore, legume production generally overlaps with the end of the wet season improving seedling establishment or partly cover the dry season, ensuring pod consumption and seed dispersal by wild animals.

In the invaded area *P. juliflora* present a different multiple possibilities of flowering, associated not only to climatological conditions, but to evolutionary associations, extremely fast, with pollinator insects. In Punjab (India) *P. juliflora* showed one flowering period from January to May with earlier flowering time period with the increase in the temperature (Kaur et al. 2013) but in the ridge of Delhi (India) *P. juliflora* flowering occurs all year round and reaches its flower peak in April and September (Thakur 1989). Flowering almost continuous year round was observed in some invaded areas as Brasil or Haiti (Silva 1988; Timyan 1996). In the Arabian Peninsula, El-Keblawy and Al Rawai (2006) reported two episodes for flowering: autumn (November – Dec.) and (April – May). However, in moist year, the plants was observed in the flowering stage of the year around. There is controversy about time development of flowers in *P. juliflora*. Styles emerge from most flowers prior to anthesis and flowers remain in this state for some days (Pasicznik et al. 2001). Anthesis occurs when flowers are fully open and accessible to pollinators. Flower maturation is variable in the same tree, often lower flowers in the raceme are fully developed than the upper ones that are still immature (acropetal succession). In

general, the main pollen season took place in spring, the highest concentrations being recorded mainly in April, with a secondary peak in autumn, if any (Davis 1995 and Simpson et al. 1977). On the other hand, Perveen et al. (2014) studied the intradiurnal behaviour followed by *P. juliflora* pollen at Khairpur (Pakistan), where the maximum peak occurred near midday, at 11:00.

7.4.2.2 *Prosopis juliflora* and Pollinators

Pollinator assemblage structure can have important influences on floral evolution and reproductive interactions among plant species (Moeller and Tiffin 2005). *Prosopis* anthers have a glandular appendage that release an exudate containing protein and carbohydrates (Chaudhry and Vijayaraghavan 1992). Then, flowers produce copious amounts of nectar, as a nutritious reward for potential insect pollinators especially bee species (Simpson et al. 1977). In a geographical context, the spatial structure of variation in pollinator abundance and community composition can also have important implications for plant reproductive performance and ultimately floral evolution (Gomez et al. 2007). This entomophilia is extremely generalized, 77 insect visitors being reported in India by the former authors, Hymenoptera (bees and wasps) and Diptera (flies) being the main visitors.

P. juliflora is self-incompatible and receives insect pollinators and entomological visitors from a wide type of insect orders (Ward et al. 1977). *P. juliflora* has small size of flowers that ensures the contact of small insects with reproductive organs and there will be less chances of nectar robbing. Despite *P. juliflora* produces large number of inflorescences; the pollination success rate is significantly less. Based on inflorescence number/tree, according to reports of DeOliveira & Pires (1990), *P. juliflora* exhibited 29% pollination efficiency while it was dropped to 1.48%. Flowers of *Prosopis* are visited by different types of insects and more specifically from Hymenoptera (bees, wasps and *Pepsis* spp.), Coleoptera (Bruchidae, Lycidae, Tenebrionidae, and Scarabaeidae), Diptera (Syrphidae), and Lepidoptera (Noctuidae, Geometridae and various butterflies) (Simpson et al. 1977; Keys 1993).

Many plant species produces mass-flowers and mostly for floral display but usually they do not have enough food resources to transport to these points that help them to develop into fruit (Trueman & Wallace 1999). However, several plants produces significant number of seeds that are enough for that particular species to survive (Karron & Mitchell 2011). Other researchers demonstrated that there are several factors responsible for productivity and includes stigma reception, pollen release time, period and pollen viability. In this regard, ovary abortion, flower sterility and few pollen visitors are others major reasons for low pollination and productivity DeOliveira & Pires (1990). In case of *P. juliflora* that mostly grown in arid and semi arid regions with high summer temperature are another reason of low pollination. The insect pollinators are less mobile during midday (above 40 °C) that coincided with higher pollen production at midday (Goel and Behl 1995). There was also significant spatial variation observed among locations in pollinator assemblages in terms of species richness, diversity and dominance. The

abundance–richness relationship is frequent in pollinator assemblages (Steffan-Dewenter et al. 2002),

According to studies of Sajjad et al. (2012), number of pods and germination rate of seeds rise with increase in its flower visitors. They concluded that flower visitor abundance was a better predictor of plant reproductive performance than species richness and the Shannon-Wiener index. We also found a significant spatial variation among locations in pollinator assemblages in terms of species richness, diversity and dominance. Diversity and identity (Gomez et al. 2010), and relative abundance of floral visitors (Sahli and Conner 2006) have been reported as the important predictors of plant reproductive success. The sensitivity of pollinator assemblages to predict plant reproductive success may vary with plant species and the pollination effectiveness of available pollinator species (Talavera et al. 2001).

7.4.2.3 Seed Production, Dispersal and Germination

The racemes work as reproduction units and the small size of the flower ensures contact of small insects with reproductive organs. Different maturation period in the reproductive organs and flowers development make *P. juliflora* plants self-incompatibles, depending of insects for seed setting (Sajjad et al. 2012). Obligate outcrossing leading to high genetic variability as an evolutionary mechanism for survival in zones with a high variability in rainfall, temperature and soil types. This trait, among others, allows to *P. juliflora* being an effective plant invader. By other hand, as was mentioned, long periods of asynchronous flower production would assume a long period of pollen release. However, due to *P. juliflora* is a tree and its flowers exhibit exerted stamens, its pollen grains present a secondary anemophily and can easily pass into the atmosphere and become airborne. Coat imposed dormancy is of wide occurrence in legumes and has been reported as a characteristic governing the weediness of *P. juliflora* (Morgan et al. 2017). In the field germination is favoured because of *P. juliflora* seeds pass through the digestive system of grazing sheep, goats and cows that might help in seed dissemination for long distances. In Ethiopia, it was observed that cattles are major source of seed disoersals followed by camels and goats (Shiferaw et al. 2004). Morgan et al. (2017) revealed that seeds collected from sheep's droppings were free from the pericarp and displayed 65% germination and 60% emergence suggesting that soil seed bank contain seeds of *P. juliflora* ready to germinate when conditions are optimal or moved to a shallower depth by agricultural implements.

The seed traits such as seed coat, endosperm, pericarp and extrafloral organs prevent germination until they are removed or damaged (Finkelstein 2006). On average, fruits of *P. juliflora* (15–20 cm width, 10–40 cm length) possess 20 seeds/pod. The endocarp is divided into rigid, leathery segments with one brown, elliptical seed in each segment (Meyer et al. 1971). The seeds frequently have hard, impermeable seminal integuments (Manga and Sen 1995), which ensure dormancy and are well adapted to long-term survival (Tschirley & Martin 1960) and dispersal strategies (Bewley 1997). Several Environmental factors such as fire, temperature,

salinity and light as well as their interaction might stimulate or retard the seed germination of *Prosopis juliflora*. Salinity stress of 400 mM NaCl at 40 °C and in 600 mM NaCl at 25 °C decreased the seed germination. Furthermore, light also stimulated the germination at low salinity (El-Keblawy et al. 2015). Autotoxicity due to dry leaves of *P. juliflora* also caused significant inhibition in germination, radicle and hypocotyl growth of mesquite seeds (Warrag 1995). Due to climate change and increase in soil temperature will results in inhibition or stimulation of certain plant seed germination (Ooi et al. 2009). Al-Rawahy and co-workers (2003), demonstrated that germination of both *Prosopis juliflora* and *P. cineraria* seeds were unaffected following exposure to 90 °C for 6 h.

Senthilkumar et al. (2005), documented that prosopis has also capacity to bioaccumulate heavy and toxic metals in various plant organs. Prosopis accumulated significant quantity of Cd in roots than shoots. While, concentration of Cu was not much distinguished between roots or shoots. They concluded that animal grazing on heavy metal contaminated soil vegetation should be avoided because the plant foliage and pods can retain more toxic metals than other parts. Several diverse animal species such as camels, goats, sheep, deer, horses, cattles, rodents, feral pigs, warthogs are also responsible for dispersal of Prosopis seeds from one place to other through their feces (Kneuper et al. 2003, Shiferaw et al. 2004). Shiferaw et al. (2004) reported germination rates for *P. juliflora* of 100% with mechanical scarification, 97–99% germination with sulfuric acid, 37% after passage through goats, 47% through warthogs, 15% through camels, 4% through cattle, and 21% with no treatment. However, El-Keblawy and Al-Rawai (2005), documented more than 80% germination success in unscarified seeds. A study conducted on anther glands of *P. juliflora* demonstrated that an exudates (composed of carbohydrates and proteins) was excreted through cuticular openings to exterior of glands and have function like insect and pollinators attractance (Chaudhry and Vijayaraghavan 1992).

The process of Endozoochory might be responsible for enhancing the germination through releasing the seeds from fruit and ruminants feces that can also serve as source of water and nutrients for seedling establishments. Local animals, cattles, goats, camals, mules and wild fauna (gazelles and coyotes) can play a significant role in dispersal of seeds from one to other places (Wronski et al. 2012; Alvarez et al. 2017). However, exposure of the seeds to animal gut microenvironment, stomach juices, chewing, and herbivores species also affect the quality of endozoochorous (Schupp (1993; Kneuper et al. 2003; Jaganathan et al. 2016). In this context, determining whether endozoochory is advantageous to plant germination requires examining the cumulative effects of gut passage, deposition in faeces and seed dispersal patterns on germination and viability. Thus, understanding the functional role of domestic and wild animal species in seed dispersal of invasive species is central to determining how biotic interactions could be affected by anthropogenic drivers.

7.5 Possible Mechanisms explaining the Invasive Ability of *P. juliflora*

The traditional, congeneric, and bio-geographical approaches have been used to examine the mechanism of invasive species success (Inderjit et al. 2008).

7.5.1 Traditional Approach

The traditional approach focuses on the fate, dose, replenishment, and effect of chemicals produced by invaders in the soil environment (Inderjit 2001; Hierro and Callaway 2003).

Allelopathy is mediated through the release of secondary metabolites that directly affects many physiological and biochemical reactions and thereby, influence the growth and development of neighboring plants (Lara-Núñez et al. 2006; Hussain et al. 2011; Hussain and Reigosa 2011). Allelopathy has been suggested as one of the mechanisms driving *P. juliflora* to become more abundant and competitively dominant in their introduced range than in their native range (Elfadl and Luukkanen 2006; El-Keblawy and Al-Rawai 2007; Inderjit et al. 2008 and Kaur et al. 2012) reducing significantly the number of annual plants under the canopy of *P. juliflora*. The plant has little or no autoallelopathic effect under field condition (El-Keblawy and Al-Rawai 2006). This mechanism, combined with drought condition can inhibit other species and eliminate any kind of competition (Abdulahi et al. 2017).

7.5.2 Congeneric Approach

The congeneric, or phylogenetic, approach involves comparative studies of exotic species with natives in the same genus (Inderjit et al. 2008). Native plants typically do not share a co-evolutionary history with the exotic invasive species, and therefore greater allelopathic effects of the alien invasive, as compared the native congeneric in such ecosystems. The allelochemicals produced by the invaders are new to the native plant communities (i.e., novel weapons, Bais et al. 2003; Callaway and Ridenour 2004). Assessment of the impact of allelopathy of two *Prosopis* species on the germination and existing of the associated species helped in understating the role of allelopathy as a mechanism for invasion of *P. juliflora* in its new ranges (El-Keblawy and Abdelfatah 2013; Kaur et al. 2012). In both Arabia and India, the native *P. cineraria* is a slow growing tree and is beneficial for the growth and development of other species (Abdel Bari et al. 2007). It is rarely, if ever, seen as a weedy species and has not been successfully introduced into other parts of the world (Pasicznik et al. 2001). In addition, *P. cineraria* had a facilitative rather than

determinantal effect on the associated flora (El-Keblawy and Abdelfatah 2013; Kaur et al. 2012). In the two regions, however, the introduced *P. juliflora* has invaded many habitats and residential area and significantly reduced the native flora diversity (El-Keblawy and Abdelfatah 2013; Kaur et al. 2012). In the introduced range of the UAE and India, both species produced allelochemicals. El-Keblawy and Abdelfatah (2015) assessed the impacts of allelopathy produced by *P. juliflora* and *P. cineraria* and soil properties on understory native plants in the arid deserts of the UAE. They found inhibitory effect for the aqueous extracts of fresh and old leaves of *P. juliflora* on the associated flora, but *P. cineraria* leaves and litter had positive effects on other native species. The quantity of the allelochemicals produced by the two species could help understanding their differential effect on the associated flora. Kaur et al. (2012, 2014) found that the amounts of phenolics and tryptophan produced by *P. juliflora* in India were significantly higher than those of *P. cineraria*. For example, Kaur et al. (2012) detected L-tryptophan in leaf leachates of both *P. juliflora* and *P. cineraria*, but the amounts were 73% higher in leaf leachate of the former than that of the latter. Similarly, Inderjit et al. (2008) compared soils collected from the rhizospheres of the two *Prosopis* species and found that soils beneath the exotic *P. juliflora* contained 63.2% higher concentrations of total phenolics than soil beneath the native *P. cineraria*. This result could explain the greater effect of *P. juliflora* litter on mortality of native Indian species, compared to litters from *P. cineraria* (Kaur et al. 2012). Similarly, aqueous extract of *P. juliflora* leaves showed negative effects on root growth of three common crop species of north-west India, whereas *P. cineraria* leaf leachate had positive effects (Kaur et al. 2012). Furthermore, Goel et al. (1989) reported greater allelopathic potential of *P. juliflora* leaf leachate and decomposing litter residues compared with *P. cineraria*.

7.5.3 Biogeographic Approach

The biogeographic approach studies ecological traits of species and ecological processes in native and non-native ranges. Exotic species bring chemicals novel for invaded communities that has potential to exhibit allelopathic effects due to naïve soil communities and sensitive neighbors (Callaway and Ridenour 2004, Inderjit et al. 2011). The ‘novel weapons hypothesis’ was posed by Callaway and Aschehoug 2000; also see Rabotnov 1982; Malik and Pellisier 2000; Ridenour and Callaway 2001) to study role of plant chemicals in ecological processes and evolutionary context (Inderjit et al. 2006, 2011). Several plant secondary metabolites (phenolics, flavonoids, glycosides, chalcones, cinnamic acid derivatives, Terpenoids, Coumarin, Saponins, and alkaloids) were reported from bark, leaves, stems, flowers, pods and seeds of *P. juliflora* (Table 7.2). Nakano et al. (2003), demonstrated the presence of phenolics, tryptophan and juliflorine from *P. juliflora* foliage. Whereas *P. juliflora* has facilitative effect in its native range in Venezuela, it has an inhibitory effect in its introduced range.

Table 7.2 Secondary metabolites isolated from different *Prosopis juliflora* organs: leaves, stems, flowers, fruit, pods, seeds, and bark

Plant part	Metabolite class	Compounds	Extract type	References	
Pollen	Flavonoids	Apigenin derivative-7-O-R	Identified in ethanol–water (50% v/v) extract by high-performance liquid chromatography/diode array detector (HPLC/DAD)	Almaraz-Abarca et al. (2007)	
		Cinnamic acids	Luteolin derivative		
			Flavonol glycoside		
			Quercetin-3-glycoside		
			Genistein glycoside or dihydroquercetin		
			Isorhamnetin-3-O-R		
			Chalcone		
Cinnamic acid derivative					
Fruits	Flavonoids	Patulitrin (flavonoid)	Fruit ethanol extract (flavonoid identification) and aqueous extract (free sugar identification)	Wassel et al. (1972)	
	Free sugars	Glucose and sucrose (free sugars)			
Bark	Flavonol glycoside	Kaempferide 3-O-b-dgalactopyranoside	Characterized in ether soluble fraction from acetone extract	Nee' Shukla and Misra (1981)	
	Isoflavone glycoside	Retusin 7-O-neohesperoside	Characterized in ethanol extract		
Leaves	Flavonoid	–	Phytochemical screening reactions analyzed by gravimetric and spectrophotometric methods	Ibrahim et al. (2013)	
	Alkaloids				
	Saponins				
	Phenols				
	Tannins				
	Fibers				
	Pectic substances				
Leaves	Flavonoids	Apigenin	Identified in standard extracts and chromatographic procedures	Bragg et al. (1978)	
		Luteolin			
		Apigenin-6,8-di-C-glycoside			
		Chrysoeriol 7-O-glucoside			

(continued)

Table 7.2 (continued)

Plant part	Metabolite class	Compounds	Extract type	References
		Luteolin 7-O-glucoside		
		Kaempferol 3-O-methyl ether		
		Quercetin 3-O-methyl ether		
		Isoharmentin 3-O-glucoside		
		Isoharmentin 3-O-rutinoside		
		Quercetin 3-O-rutinoside		
		Quercetin 3-O-diglycoside (glucose and arabinose)		
Leaves	Terpenoids	–	Phytochemical screening reactions on methanol, ethanol, chloroform and benzene extracts	Sharmila et al. (2013)
	Phenol			
	Flavanoid			
	Coumarin			
	Glycoside			
	Carbonyl			
	Saponins			
Leaves	Pigments	Carotene, xanthophylls and pheophytin	Identificated in etanol extracts	Tesoriere et al. (2005)
Pods	Ellagic acid glycoside	Ellagic acid 4-O-a-L-rhamnosylgentiobioside	Isolated in ethanol extract	Malhotra and Misra (1981c)
Pods	Ellagic acid glycoside	Ellagic acid 4-O-rutinoside	Isolated in ethanol extract	Malhotra and Misra (1981b)
Pods	Tannins	Tannins	Different solvents extracts as acetone and methanol	Makkar et al. (1990)
Roots	Flavanone glycosides	30,40-dihydroxy 5-methoxy 6-methyl flavanone 7-0-b-D-glucopyranoside	Isolated in benzene and ethyl acetate fractions of ethanolic	Malhotra and Misra (1983)
Roots	Ellagic acid glycoside	3,30-di-O-methyl ellagic acid 4-O-a-Lrhamnopyranoside	Isolated in acetone extraction	Malhotra and Misra (1981a)
Seed	Amino acids	Essential amino acids except lysine, methionine and cysteine	Hydrothermically processed seed meal	Bhatt et al. (2011)

Costa et al. (2018), reported the ecological damage to ecosystems, stand stabilization and settlement of *P. juliflora*. The leaves, barks and roots (aqueous extracts) (125 g plant/500 ml of distilled water) inhibited the emergence and seedling growth of jurema-preta, *Mimosa tenuiflora*, native species of Caatinga and 100% root extract proved to be deleterious than all other extracts. Shah et al. (2018), in a

two-year field experiments demonstrated the phytotoxicity of *P. juliflora* on weed control and yield of wheat. They found that aqueous extracts (0, 10, 20, 30 and 40% concentration of leaves, stems, and roots) reduced the weed density, biomass, leaf area index, leaf area duration, crop growth rate, net assimilation rate, chlorophyll contents, plant height, number of tillers, spike length, number of grains, 1000-grain weight, grain yield, biological yield, harvest index and grain protein content.

Prosopis juliflora is known to inhibit germination of seeds of other plants species that lie in its vicinity (Muturi et al. 2017; Shaik & Mehar 2015). It also discourages other species of plants to grow near it. It releases allelochemicals from its leaves, roots, as well as fruits to achieve this (Noor et al. 1995). Goel et al. (1989) found that leaf extracts as well as leaf leachates of *P. juliflora* carried allelochemicals, so did decaying leaves. These authors, as well as Chellamuthu et al. (1997), who studied the influence of *P. juliflora* leaf litter on the germination of seeds of other species, attributed the allelopathy to phenolic compounds present in *P. juliflora*. Al-Humaid and Warrag (1998) recorded suppression of seed germination and early growth of bermuda grass (*Cynodon dactylon*), and Kaur et al. (2014) of *Brassica campestris*, by aqueous extracts of *Prosopis* leaves. These studies indicate that *P. juliflora* foliage may contain water-soluble allelochemicals, which get leached to the ground as rain water falls on them and trickles down (Abbasi and Abbasi 2011). These chemicals were isolated by Nakano et al. (2002, 2003, 2004) and identified as syringin, (-) – laricresinol, L- tryptophan, juliprosopine, juliprosine, and juliprosopinal. Among these, juliprosine derivatives exhibited the most pronounced allelopathy.

This indicates that allelopathy plays a significant role in shaping plant community structure. In its native range in Venezuela, *P. juliflora* appear to coexist with and facilitate large numbers of other native species (Kaur et al. 2012). In its non-native ranges, *P. juliflora* strongly suppress species native to those regions (Pasiczchnik et al. 2001) and forms pure stands in India, Hawaii (USA) (Kaur et al. 2012) and the UAE (El-Keblawy and Al-Rawai 2007). Competition is another mechanism that would enable *P. juliflora* to replace native flora. Root density of *P. juliflora* was 3 cm of root/cm³ of soil in the upper 15 cm of the soil profile, dropping to less than 0.5 cm root/cm³ of soil at below 45 cm depth, and less than 0.2 cm root/cm³ of soil at 1.8 m depth (Jones et al. 1998). Hoshino et al. (2011) indicated that *P. juliflora* can detect even very tiny soil moisture and grow to various conditions. Some of the many adaptive abilities that allow *P. juliflora* to thrive under such conditions include ability of roots to adapt to a wide variety of soil conditions (Hoshino et al. 2011). Roots can grow upwards towards the soil surface to capitalize on little rainfall, but can also grow to depths of 80 m and extend laterally more than 30 m (Thorp and Lynch, 2001). Such high density of the superficial roots could enhance the competitive ability of *P. juliflora* to extract the limited nutrients and water resources of the arid deserts (El-Keblawy and Abdelfatah 2014). This could explain the high aggressive ability and how it could crowd out native vegetation in most invaded sites. It has been noticed that farmers in many places of the UAE just ruin their farms once they are invaded with this species.

Shirke et al. (2018) demonstrated that *Prosopis juliflora* has shown optimal physiological characteristics to adapt in monsoon season through its leaf architecture

that exhibit maximum carbon fixation under moderate temperatures and a wide range of photosynthetic photon flux density. The leaves produced in spring were sensitive to very high temperature and others that develop during monsoon were sensitive to low temperatures causing senescence in winter. Reinoso et al. (2004) found that salinity induced anatomical changes in roots (young and mature zones), hypocotyls, young stems, and leaflets, with small leaves, reduced cortex and vascular system. Salt stress was also lethal for stem and in hypocotyl size, diameter was reduced along with a reduction in secondary phloem. However, salinity stimulated the production of tannins in stem and leaflets of treated plants. They concluded that anatomical modifications in this species are related to metabolic adaptations, such as an early development of the endodermal barrier for ion exclusion, to allow survival in high salinity.

7.6 Impacts of *Prosopis* Invasions on Biophysical Features and Ecosystem Services

Prosopis juliflora can grow in different arid climates and substrates because of its resistance to drought and heat and it has many potential uses and impacts (Mendes 1986).

7.6.1 Uses and Positive Impacts

In some areas the benefits from *Prosopis* are regarded as a key income source for many households. For example, 44% of people in a village in Malawi relied on *Prosopis* products as a primary or supplementary source of income (Chikuni et al. 2004). Similarly, sale of charcoal and *Prosopis* pods for fodder have enhanced the local economy in some areas in Kenya by US\$1.5 million per year (Choge et al. 2012). In India, *Prosopis* provides up to 70% of fuel wood needs for local households in some dry region villages (Pasicznik et al. 2001). In Senegal, the positive aspects of *P. juliflora* are predominantly associated with regulatory services, such as soil erosion regulation, rehabilitation of sodic soils, flow regulation, and water purification (Tripathi and Singh 2010). The dense shrubs of *P. juliflora* stabilize the soil, regulate the flow of water, and promote the infiltration of water into the soil. The dense shrubs also provide physical protection to soils against wind erosion during dry periods and against heavy rains during the rainy seasons (Ayanu et al. 2015).

Prosopis juliflora increase organic matter and nutrients on soil beneath its canopy, and commonly used to improve soil physiochemical and biological properties (Vallejo et al. 2012).

Secondary products from *P. juliflora* includes honey, edible exudates gums, fibres, tannins, foliage for fodder, mulch, biopesticides and medicines, and other

uses for wood and particle board, wood chips for energy generation, pods for ethanol production, galactomannan gums from the seeds and other specialist products (Wise et al. 2012; Oduor and Githiomi 2013; Haji and Mohammed 2013).

7.6.1.1 Pods Can Be Used as a Livestock Feed and for Making Human Foods

The pods of *P. juliflora* contain high levels of protein and are available for a minimum of 4–5 months in the UAE. This could be a good source for proteins for livestock. However, the low digestibility of the leaves and pods of *P. juliflora* is mainly associated with the presence of harmful substances, such as tannins, glucosinolate, cyanogens, alkaloids, and nitrates (Chaturvedi and Sahoo 2013; Leonard 2011). In some cases, some ruminants are spontaneously poisoned and intoxicated by pods of *P. juliflora* (Camara et al. 2011). In addition, the dried leaves of this species suppress feed intake and nutrient availability and shouldn't be included in the feed of livestock (Chaturvedi and Sahoo 2013). An overview of use of *Prosopis juliflora* and its different organs in livestock feed was elaborated in Table 7.3.

P. juliflora was assayed as biosorbent due to their extremely rapid proliferation, massive growth, renewability, high biosorption capacity and low cost. Seed powder of the *P. juliflora* exhibit an ability to absorb Pb (II) from the contaminated environment (Jayaram and Prasad 2009). Biomass contributes a significant share of global primary energy consumption because liquid fuels produced from biomass contain no sulphur, thus avoiding SO₂ emissions and also reducing emission of NO_x (Kumar and Kotiya 2004). The *P. juliflora* was used as a potential renewable energy source and their large scale utilisation can represent one of the best strategies for their management. The fermentation of both acid and enzymatic hydrolysates, containing 18.24 g/L and 37.47 g/L sugars from *P. juliflora*, with *Pichia stipitis* and *Saccharomyces cerevisiae* produced 7.13 g/L and 18.52 g/L of ethanol with corresponding yield of 0.39 g/g and 0.49 g/g, respectively (Gupta et al. 2009). *P. juliflora* was used for extraction of energy precursors in the form of volatile fatty acids (VFAs). Patnaik et al. (2018) in a single one-pot step, were able to convert up to 10.7% of the total solids present in the *Prosopis* leaves to VFAs.

7.6.2 Negative Impacts

7.6.2.1 Aboveground Effects

Maundu et al. 2009 studied the negative aspects of *P. juliflora* on local livelihoods of three sites in Eastern Province of Kenya and reported 24 negative effects. The magnitude varied according to people's sources of livelihood. The aspect that caught most attention in all sites was the thorn problems on humans. Several problems are related to animals that depended heavily on the pods. In addition, diarrhoea is

Table 7.3 Use of *Prosopis juliflora* and its different organs in livestock feed

Type of study	Key findings	References
Digestibility of globulins from mesquite pods and cowpea by mammalian digestive enzymes.	Pods were difficult to digest due to the presence of globulins, in comparison to immature cowpea.	Araujo et al. (2002)
Pods in the diets of laying hens	The pods can be included upto 13.6% of the diets without adversely affecting the performance of the laying hens.	Vilar Da Silva et al. (2002)
Prosopis flour in diets of rats	Due to the protein content present in the flour, there was no adverse effect during pregnancy and lactation phases.	Da Silva et al. (2003)
General feed for livestock.	Pods could replace costlier feed ingredient such as grain and bran, contributing 10–50% of the diet. If the percentage increases to 20%, then phosphorous supplements need to be added	Sawal et al. (2004)
Pod meal in the diet of growing crossbred heifers along with wheat straw.	Complete feed with 30% wheat straw and 20% Prosopis pods replacing rice polish, can be given as feed to heifers, without an adverse effect on growth and reproduction.	Pandya et al. (2005)
Pods as a feed for goats	Pods can be utilized as feed up to a proportion of 200 g–1 kg of rhodegrass hay. Higher pod fraction affects the carcass yield and quality.	Mahgoub et al. 2005
Pods as a meal for horses.	Pod meal can be used in the diets of horses even though a decrease in dietary fiber digestibility is seen.	Da silva stein et al. (2005)
Pods as a feed for Awassi lambs	Upto 200 kg–1 replacement of barely grains with pods is feasible, and is also cost effective. More than that will affect the growth, digestibility, and quality of the meat of the lambs.	Obeidat et al. (2008)
Pods as a feed for Nile tilapia fries.	Diet supplemented with 60 g kg–1 pods improved the growth, nutrient utilization and whole body composition in Nile tilapia fry.	Mabrouk et al. (2008)
Pod meal in diets of lactating goats	Substitution of corn meal by pod meal had no significant effect on the ruminal parameters but showed a linear negative response for microbial efficiency synthesis	Argolo et al. (2010)
Pods as a feed ingredient in the diets of broiler chicks	Pods can replace corn by 20% in the diet of broiler chickens.	Al-Beitawi et al. (2010)
Prosopis seed meal for Labeo rohita fingerlings	Processed seed meal can be incorporated into the carp diet at an inclusion level of not more than 20%.	Bhatt et al. (2011)
Ground pods as feed ingredient in poultry diet (broilers).	About 20% of the broilers' diet can be replaced by ground pods which will reduce feed cost without any negative effect. More at 20%, will affect the feed intake, growth and carcass quality	Girma et al. (2011)

(continued)

Table 7.3 (continued)

Type of study	Key findings	References
Ground pods as feed ingredient in poultry diet (layers).	Upto 20% ground pod in layers' ration is recommended, even though 10% is better suited. But more than 20% results in reduction of egg production and egg mass.	Girma et al. (2011)
Pods as feed for sheep and goats	Pods can be used without restriction in the feed of sheep but goats may be kept in Prosopis invaded areas for no more than one fructification period	Riet-Correa et al. (2012)
Pods and leaves as feed for lambs.	Pods can be used as a supplement in the diets of lambs without any adverse effect. However, leaves are unpalatable.	Ali et al. (2012)
Ground pods as feed ingredient broilers	Upto 30% inclusion of ground pods in broilers diet did not alter the chemical and fatty acid composition and sensory test of the meat. But at high levels the immune response to parasitic infection was impaired	Girma et al. (2012)
Pods as feed for cattle and horses	Despite their toxicity, pods can be used as cattle feed at concentrations of 30% of the food. Horses can be given pods as diet in confined and semi-confined systems. Horses are not recommended to be kept in grazing areas where Prosopis is in fructificating whereas cattle can be kept, butfor no more than 30 days.	Medeiros et al. (2012)
Assessment of nutritive value of pods of Prosopis along with some other plants.	Prosopis along with leucaena and blue panic plant might be promising alternative feed supplement for ruminants to replace alfalfa. Prosopis had the highest volatile fatty acids concentration.	Allam et al. (2012)
Prosopis pod meal in the diet of sheep	Pod meal can replace grass upto 45% in the diet	Pereira et al. (2013)
Prosopis pod meal in the diet of lactating goats.	Pod meal can replace corn not exceeding 40.5% of the total diet.	Pereira et al. (2013)
Pods as feed along with cenchrus grass for sheep.	Pods can replace 40% of the feed mixture in sheep without any adverse effect	Chaturvedi and Sahoo (2013)
Prosopis seeds in the diets of broiler chickens	Upto 2% of the diet of broilers can have Prosopis seeds. More than that will have adverse effect	Mohammadi et al. (2013)
Partial substitution of barley grain with Prosopis pods in lactating ewes's diets	Pods can be included in the diet of nursing ewes and their lambs, to reduce the cost of feed and improve milk production, upto 250 g kg ⁻¹ .	Obeidat and Shdaifat (2013)
Replacement of cottonseed meal with ground Prosopis pods as a supplementary feed for sheep	Compared to feeding hay alone, supplementing the feed with cottonseed meal and Prosopis pods is a better feeding strategy	Yasin and Animum (2014)
Substitution of corn for pod meal in lambs' diet.	At a substitution level of 47.5%, maximum weight gain is seen in the lambs	Pereira et al. (2014)

(continued)

Table 7.3 (continued)

Type of study	Key findings	References
Preference and ingestive behavior of sheep feed on tropical tree fruits	The fruits of <i>Prosopis</i> were 'highly preferred'	Pinto-Ruiz et al. (2014)
<i>Prosopis</i> pods as a partial replacement of corn in the diet of growing broiler chicken.	<i>Prosopis</i> pods can be included at levels of 5% in broiler diets without affecting performance	Al-Marzooqi et al. (2015)
<i>Prosopis</i> pod meal in the diet of sheep	Diet consisting 30–45% of pod meal can be given to sheep.	dos Santos et al. (2015)
Pods as a replacement to concentrate feed for goats	Up to 40% of the concentrate feed can be replaced with <i>Prosopis</i> pods without any adverse effect	Hintsu et al. (2015)
<i>Prosopis</i> pods as a replacement of corn in the diet of juvenile Nile tilapia.	<i>Prosopis</i> meal can completely replace corn in Nile tilapia juvenile diets during periods of low water temperature	Silva et al. (2015)
Milled mature <i>Prosopis</i> pods as a replacement of maize in the diet of broiler chicken	Milled <i>Prosopis</i> pods negatively affected the performance of the broiler chickens.	Odero-Waitituh et al. (2016)
<i>Prosopis</i> pod meal as a total replacement of corn in the diet of Holstein-Zebu crossbred dairy steers.	<i>Prosopis</i> pod meal can totally replace corn in the diet of Holstein-zebu crossbred dairy steer.	De Oliveira Moraes et al. (2016)

happen among inexperienced goats that feed on the leaves for the first time. Furthermore, diarrhoea in goats was reported mainly in Loiyangalani town due to influx of pastoralists and their goats escaping drought and insecurity caused by raids for stealing animals. Encroachment was most serious in Baringo and Garissa sites where the species had displaced farmers from their crop farms, invaded areas used for grazing and browsing. Moreover, encroachment to paths, dwellings, water sources, farms and pastureland, constraining movement and other activities were reported as problems associated with the introduction of the species.

Vegetation and Community Structure

Several reviews have shown deserts to be among the least-invaded ecosystems worldwide, at least in terms of the number of naturalized and invasive species (Lonsdale 1999). However, this species is expanding its range at an alarming rate and damaging native diversity and ecosystem health of the arid and hyper-arid regions. It discourages abundance, richness and growth of native species. *P. juliflora* often observed to form pure stands, and does not allow other species to grow beneath or around its canopies. Despite *P. juliflora* is a strong facilitator in the native range (Tiedemann and Klemmedson 1973; Kaur et al. 2012); it was found that the

canopies of the invasive *P. juliflora* had far fewer understory species in the invaded areas than native congeners (Aggarwal et al. 1976). In the Arabian Peninsula the invasive has strong negative impacts on native species: number, richness, evenness, density and frequency of the associated native species despite increases in the concentrations of some nutrients in subcanopy soil (El-Keblawy and Al-Rawai 2007). Especially important is that this depressive effect extended beyond the canopy-covered ground for dense sites. Old and dense sites of *P. juliflora* resulted in significantly lower density, frequency and diversity for most associated annual species (El-Keblawy and Al-Rawai 2007). Similarly, the growing of *P. juliflora* shrubs, as well as exotic *Eucalyptus*, in the forests of the UAE has also resulted in significant reductions in species diversity and abundance of understory species, compared to the native *P. cineraria* and *Acacia arabica* (El-Keblawy and Ksikisi 2005).

7.6.2.2 Belowground Effects

Soil Microorganisms

Soil microbial communities play an important role in the invasion success of exotic plant species (Inderjit and van der Putten 2010). Plant-soil feedbacks (PSFs) include plant-mediated changes in soil communities that affect the establishment and growth of plant species (van der Putten et al. 2013, Inderjit and Cahill 2015). Exotic invaders are known to culture soil biota that exert neutral or positive impacts on the invader compared to the negative impacts of soil biota cultured by native species on themselves (Callaway et al. 2004). The effect of *P. juliflora* on soil properties could be mediated through soil microbial flora. *P. juliflora* trees have the potential to establish a symbiotic relationship with N-fixing Rhizobium bacteria, which increase the N levels in the rhizosphere with root and nodule turnover (Reyes-Reyes et al. 2002; Perroni-Ventura et al. 2010). For example, a total of 150 bacterial strains were isolated from the root nodules of *P. juliflora* growing in soils collected from Marigat area of Kenya (Otieno et al. 2017). In addition, the microbial activity of *P. juliflora* as witnessed by the emission of CO₂ was larger for soil sampled under canopy than outside it (Herrera-Arreola et al. 2007). Those authors indicated that addition of leaves increased production of CO₂ and between 40% and 50% of the organic C of the leaves was mineralized. Prosopis has been recognized as a fertility island tree that significantly increase soil nutrient concentration under its canopy, and improve soil microbial activity and diversity (Abril et al. 2009; Vallejo et al. 2012). The organic matter inputs from leaf litter, fruit, and root exudates returned to the soil all could increase organic C and nutrients under canopy trees. Therefore, soil beneath the *P. juliflora* canopies had higher organic C, total N, nitrate, available P and lower bulk density than soil outside, improving chemical and physical soil quality, even in the arid deserts in which water is a limiting factor for decomposition process (Vallejo et al. 2012; El-Keblawy and Abdelfatah 2013; Kaur et al. 2012). This was attributed to organic matter build-up, higher biological activity, and improved soil structure (aggregation and porosity) favored by tree roots as well as fungal and actinomycetes

hyphae. As *P. juliflora* produce allelochemicals that interfere with understory native plants and at the same time enhance soil and microbial activities, the relative importance of these two processes determines the structure of the plant community under and around the native and exotic trees (Callaway and Walker 1997).

Water and Soil Fertility

Several authors have considered the increasing number of introduced or invasive species as a major component of global change because of their potential to alter primary productivity, decomposition, hydrology, nutrient cycling, and natural disturbance regimes (Pyšek et al. 2012). The conversion of barren sand dunes in the arid deserts into dense thickets of *P. juliflora* can generate many environmental consequences through altering water and nutrient cycling, changing carbon storage and enhancing climate variability.

Considering that water is the limiting resource for the ecosystem in semi-arid and arid regions, hydrological response to *P. juliflora* invasion may directly impact the availability of ecosystem services and consequently human wellbeing (Nie et al. 2012; Vaz et al. 2017). Groundwater, which is the main water source in semiarid regions, is severely and increasingly threatened. Consequently, the greater ability of *P. juliflora* to deplete the ground water would threaten the groundwater resource and consequently affect native plants. Nie et al. (2012) assessed hydrological consequences of *P. juliflora* invasion in the upper San Pedro watershed (U.S./Mexico) and found that the simulated average annual evapotranspiration increases with *P. juliflora* encroachment, leading to the decrease of annual water yield and percolation by 9.8% and 9.7%, respectively. Therefore, *P. juliflora* increase water demand from soil, especially in the arid regions, where the limited non-renewable groundwater is depleted and/or salinated (Murad et al. 2007, AlRukaibi 2010). The deep taproot system of *Prosopis* has been implicated in declining ground water tables in Hawaii (Richmond and Mueller-Dombois 1972). Similarly, the decline in the groundwater level in the island of Kahoolawe was attributed to the spread of *P. pallida* (Stearns 1940).

Dzikiti et al. (2017), documented the impact of removing *Prosopis*, co-occurring with indigenous trees, *Vachellia karroo* (Hayne) Banfi & Galasso on the groundwater characteristics in the Northern Cape (South Africa). They measured the water consumption of both tested species through stem sap flows and found that *Prosopis* transpire 5 times more water than *V. karroo*. Following the removal of invasive *Prosopis* from the area demonstrated that water table decline was significantly slow down. The *P. juliflora* has largely invaded alluvial floodplains in North Cape, uplands, and shrub lands in South Africa and competing with native species (Mucina and Rutherford 2006). The study suggests that clearing of invasive *Prosopis* would conserve groundwater in the arid parts of South Africa (Dzikiti et al. 2013). It has been observed the *P. juliflora* is mainly invading the lands that have shallower water tables in the UAE (El-Keblawy and Al-Rawai 2007). This tree relies mainly on ground water as a main source in the absence of rainfalls. After rainfall, the

extensive superficial dense root system enables it to extract the available water, which should be at the expense of the associated native plants (Pasiczник et al. 2001).

Several studies have assessed soil physical and chemical characters under *P. juliflora* canopies and in bare ground next to them and concluded that the growth of this species improves some soil physical and chemical properties. For example, Menezes et al. (2002) indicated that *P. juliflora* in semiarid northeastern Brazil significantly affected microclimate and the dynamics of litter and soil nutrients, and may contribute to increases in the cycling rate of nutrients in these systems. In addition, Garg and Singh (2003) have shown that nutrient concentrations (N, P, K, Ca and Mg) of *P. juliflora* stand were significantly greater than that of other woody species. Furthermore, Goel and Behl (1999) reported that *P. juliflora* plantation resulted in a marked decrease in soil pH and sodium content, and improved organic carbon, N, K and P concentrations of the soil. In the arid climate of the UAE, canopies of *P. juliflora* increased the most important macro-nutrients K, N and P and the organic matter contents (El-Keblawy and Al-Rawai 2007; El-Keblawy and Abdelfatah 2014). The increase in organic content could increase the water holding capacity that would improve soil texture and increase soil moistures (El-Keblawy and Abdelfatah 2014). The effect of *P. juliflora* on soil properties could be mediated through soil microbial flora. For example, *P. juliflora* trees have the potential to establish a symbiotic relationship with N-fixing Rhizobium bacteria, which increase the N levels in the rhizosphere with root and nodule turnover (Reyes-Reyes et al. 2002; Perroni-Ventura et al. 2010). The organic matter inputs from leaf litter, fruit, and root exudates returned to the soil all could increase organic C and nutrients under canopy trees. Therefore, soil beneath the *P. juliflora* canopies had higher organic C, total N, nitrate, available P and lower bulk density than soil outside, improving chemical and physical soil quality, even in the arid deserts in which water is a limiting factor for decomposition process (Vallejo et al. 2012; El-Keblawy and Abdelfatah 2013; Kaur et al. 2012). This was attributed to organic matter build-up, higher biological activity, and improved soil structure (aggregation and porosity) favored by tree roots as well as fungal and actinobacteria hyphae.

7.7 Control Through Utilization

The high costs of *P. juliflora* eradication have argued several countries to follow a new and less expensive approach known as control through utilization. It has been argued that the negative impacts of *P. juliflora* invasion in Ethiopia are partially offset by provisioning of firewood and charcoal production. Wakie et al. (2016) have assessed the economic feasibility of selected *P. juliflora* eradication and utilization approaches that are currently practiced in Ethiopia. Their results showed that conversion of the infested area of *P. juliflora* to irrigated cotton reduces the spread of *P. juliflora* on farmlands and is economically feasible. In addition, managing *P. juliflora* infested lands for charcoal production with a four-year harvest cycle is also profitable (Wakie et al. 2016). However, the difficulties to control its rapid

spread indicate that the threats it poses to ecosystem services, people's livelihoods and lifestyles may exceed its benefits (Ayanu et al. 2015).

The plant biomass that is rich with high lignin content results in high biochar yields (Sohi et al. 2010). The major component of mesquite wood was lignin (63.96%), which makes it a potential source for biochar. Li et al. (2016) used the mesquite wood to produce three biochars with different pyrolysis conditions (no pyrolysis, 450 °C, or 750 °C). Among the three pyrolysis conditions, biochar pyrolyzed at 450 °C showed a moderate yield (40 wt%), the highest surface area (500 m² g⁻¹), the highest pore volume (1.02 cm³ g⁻¹) and the highest CO₂ uptake (26 mmol g⁻¹) at 30 bar and 25 °C. When the pyrolysis was done at 700 °C, the yield of the activation reaction (63 wt%) was considerably higher. However, the CO₂ uptake performance (13.9 mmol g⁻¹) was much lower (Li et al. 2016). The yield of biochar produced by mesquite was 44.4% with pyrolysis temperature of 400 °C (Liu et al. 2016). The C content of the biochar depended on mesquite feedstock particle sizes; small particle sizes (<0.853 mm) produced higher C (68%), compared to larger particle sizes (1.70–2.00 mm) that produced (73%) (Liu et al. 2016). In addition, pH depended on particle sizes; small particle sizes (<0.853 mm) produced pH = 7.95, but larger particle sizes (1.70–2.00 mm) produced lower pH (7.41, Liu et al. 2016). The acidic nature of biochar produced from *P. juliflora* makes it perfect for nutralizing the calcareous alkaline soils of the arid deserts. In addition, biochar can improve the physical and chemical properties of low quality sandy and marginal soils that devoid of nutrients and have very low water holding capacity (Cao et al. 2009). Many studies have shown that biochar, in different soils, is a useful resource to improve the physicochemical properties of soil, effectively maintain soil organic matter levels, increase fertilizer-use efficiency and increase crop production, particularly for long-term cultivated soils in subtropical and tropical regions (Lehmann et al. 2003). As biochar is a carbon-rich solid product of thermal stabilization of organic matter, it could be stored safely as a carbon source in soil, which could control Co2 emission and consequently is good solution for global warming.

7.8 Conclusion

The exotic invasive *P. juliflora* is threatening the ecosystem services and human well-being. The species has introduced to combat desertification in different places around the world, but became one of the factors causing land degradation. In the native range, it has very limited effects on ecosystem components and native plants, but came with their new weapons, such as new allelochemicals and may be some endophytic bacteria that helped them to have serious impacts on the native flora of the introduced range. *P. juliflora* invasions have led to changes in ecosystem services, ground water depletion, plant biodiversity loss and alteration in soil physicochemical properties. The widespread of *P. juliflora* and modification of its phenology to flower more than one episode per year enable it to cause serious health threat, such as allergies. A change in hydrological cycles associated with *P. juliflora*

invasion has aggravated the drought episodes that will be further exacerbated due to future climate change scenarios. However, *P. juliflora* introduced several economic and environmental benefits in the introduced range, such as soil conservation, fuel-wood, livestock fodder, timber, and fiber. It is important to calculate the beneficial and harmful impacts of *P. juliflora* and consequently take the decision whether to eradicate or conserve it. Allelochemicals produced by this species would affect the associated soil microbial communities, which in turn might have negative feedbacks for nutrient cycling, ecosystem processes and native vegetation. Further studies are needed to assess the impact of the introduced allelochemicals on local microbial communities. In the introduced range, where the plant has now become naturalized and became part of the flora, the threats posed by *P. juliflora* have been identified and control actions are currently implemented at both national and regional levels to reduce the deleterious effect of this species on the environment and human health. Regional regulations, prevention of expansion, knowledge platforms and environment protection laws are some of the crucial steps that needs to be undertaken for exotic species control measures and further spread and naturalization. In stipulations of the appraisal of native plant communities, functional traits should be assessed for understanding different mechanisms of controlling this plant.

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Conflict of Interest The authors declare that they have no conflict of interest.

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