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Prosopis **encroachment along the Fish River at Gibeon, Namibia. I. Habitat preferences, population densities and the effect on the environment**

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Abstract

Prosopis *species have been introduced into Namibia in the early 20th Century, and have since invaded especially the riverine ecosystems. Within the frame of the project "A Water Secure Future for Southern Africa" a baseline study to the* Prosopis *infestation near Gibeon was undertaken to determine the effect of the infestation on the ecosystem, and to propose possible ways to combat this infestation.*

For this paper a baseline floristic survey of the invested areas is presented, using the Braun-Blanquet survey method. In addition the population density was determined using a belt transect method over 4 x 100 m. Mapping using aerial photographs from 2010 with a ground resolution of 0.5 m was done to determine the spatial extent of the identified habitat types (commonage, floodplains, river bed, and riparian thickets).

Three plant communities were identified: Acacia nebrownii *shrubland within the upper slope of the commonage,* Tetragonia schenkii *shrublands on the floodplains, and* Tamarix usneoides *woodland along the river banks and in the fountain area. The latter can be subdivided into three units based on structure and habitat. The population of* Prosopis *at Gibeon is strongly regenerating with the smaller trees and shrubs (<3 m) dominating the stands. The river bank habitat (riparian thickets) had the highest density of over 2,500* Prosopis *plants/ha followed by the fountain habitat with over 900* Prosopis *plants/ha. Water use by the plants was estimated for the individual habitats based on the measured densities and size class distribution, and the total water use by* Prosopis *for the study area is estimated at 1.2 M* m^3 *per annum for the study area.*

Prosopis *plants have largely replaced the natural vegetation along the Fish River, with only remnants of the original vegetation remaining. This invasion poses a major threat to the ecosystem and its functioning. The water used by the alien vegetation is considerably higher than natural vegetation would have used, and it is estimated that roughly 18% of the potential influx of the new Neckartal Dam in the lower Fish River is lost due to the* Prosopis *infestation.*

Keywords: Alien invasive species; ecohydrology; Nama-Karoo; riparian thickets.

Introduction

Three species of *Prosopis* were introduced in Namibia during the early 20th Century, being *Prosopis chilensis, Prosopis glandulosa* (with two subspecies, *P. glandulosa* subsp.

glandulosa and *P. glandulosa* subsp. *torreyana*) and *Prosopis velutina*. It is believed that a German settler planted the first *Prosopis* trees for shade and as fodder trees for domestic animals such as cattle, donkeys, horses, goats and sheep. By 1912 the tree was reported to have established itself in the wild (Brown *et al.* 1985; Smit 2005). The first invasion of *Prosopis* in Namibia was recorded in 1950, when a group of farmers took over a large part of Southern and Central Namibia (Smit 2005). It has spread rapidly since in areas such as the Swakop River (Visser 1998) as well as the Nossob and Auob Rivers (Brown *et al.*, 1985). In the mean time, *Prosopis* species are labelled as the invasive species of greatest concern in Namibia (Brown *et al.* 1985; Bethune *et al.* 2004; Smit 2005).

Prosopis is able to flourish in wide spectra of rainfall patterns with mean annual rainfall ranging from 100 mm or less, up to 1,500 mm (Pasiecznik *et al.* 2001). However, they are less likely to be found in areas with mean annual rainfall more than 1,000 mm. *Prosopis* spp. have a wide ecological amplitude and are adapted to a wide range of soil types from dune sands to cracking clay (Pasiecznik *et al.* 2001). *Prosopis* are found mostly growing in soils such as sandy arenosols, shallow limestone and even in poor saline or alkaline soils, but more commonly on gravely leptosols. *Prosopis* usually colonises disturbed, eroded, over-grazed or drought affected areas (Smit 2005).

Prosopis are known to be phreatophytic plants (Le Maitre *et al.* 1999; Hultine *et al.* 2003; Smit 2005; van den Berg 2010), meaning they obtain a considerable amount of their water from the unsaturated zone above the water table in the soil. *Prosopis* are able to survive in areas with extremely low rainfall or a lengthy period of aridity, provided that the taproot is able to reach the groundwater within its first few years. The habitat of *Prosopis* has been described as areas with relative deep soil with underground water table close to the surface such as river banks, pans and depressions. The density of *Prosopis* invasion has been found to be highest close to river banks and decreases away from the river (Schachtschneider & February 2010). Various studies (Boyer & Boyer 1989; Smit 2005; van den Berg 2010) have indicated *Prosopis* as a wasteful water consumer. Levitt *et al.* (1995) measured water consumption for 3 m tall *Prosopis alba* trees and found that they use between 0.35 and 5.5 l/day.

Visser (1998) found that in the Swakop River, *Prosopis* density was increasing at the expense of local plant species richness. The species that are mostly affected are ephemeral river species such as *Acacia erioloba* in the Nossob River and *Faidherbia albida* in the Swakop River (Bethune *et al.* 2004).

As part of the project ‘A Water Secure Future for Southern Africa’, within the Orange-Senqu River Basin, the Desert Research Foundation of Namibia (DRFN), with funding from the United States Agency for International Development (USAID), is seeking solutions for the invasion problem of *Prosopis* at Gibeon along the Fish River in central southern Namibia. This paper attempts to understand the population dynamics of *Prosopis* and other woody species in the study area as well to appreciate any degradation, major threats, and conservation needs within the study area, and to determine possible remedial actions, which includes harvesting of fire wood. With this first paper, the preferred habitats of *Prosopis,* the density of the *Prosopis* stands, as well as their effect on the riparian ecosystem, are described.

Study area

The study was conducted at Gibeon (S 25°07.5′, E 17°46.0′) in the Hardap region along the Fish River (Figure 1), which is part of the Orange-Fish River Basin in the southern central part of Namibia (Strohbach 2008).

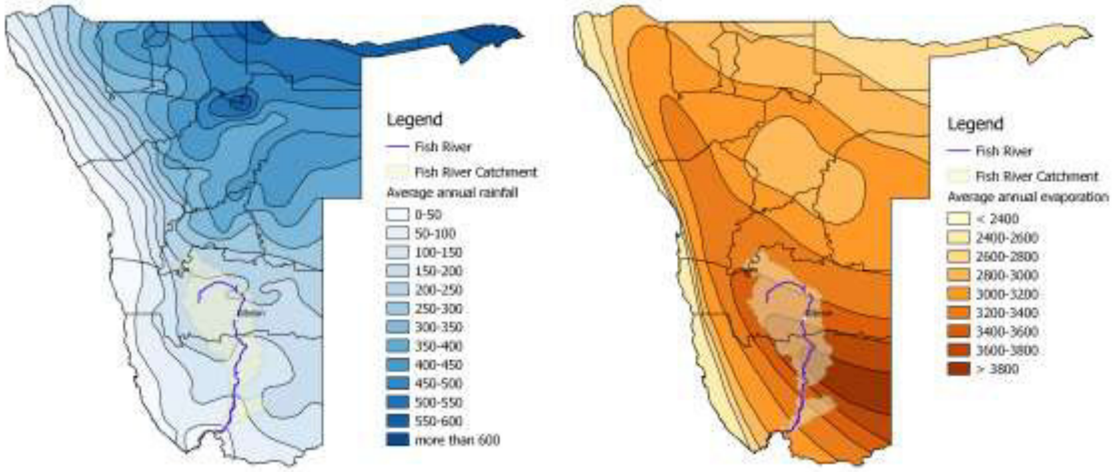

Figure 1. Location of Gibeon, in relation to the Fish River catchment (shaded) and the prevailing climate. (a) Mean annual precipitation (mm) and (b) mean annual evaporation (mm). Source: Mendelsohn *et al.* (2002); Strohbach (2008).

Climate

The south central areas of Namibia are characterised by a typical subtropical desert climate (Bw) following Köppen (1936). The mean annual rainfall ranges between 150 and 200 mm, with a 70% – 80% coefficient of variation (Mendelsohn *et al.* 2002). It rains predominantly during late summer, between February and April (Botha 1996). This region is among the hottest regions in the country, with average maximum temperature soaring to well above 36°C in summer and average minimum temperature sinking to below 2°C in winter. Evapotranspiration for this area ranges between 3,400 and 3,600 mm per annum (Mendelsohn *et al.* 2002).

Geology and soils

The Fish River catchment falls within the Nama Group in southern Namibia (Geological Survey 1980). This geological group consists of fluvial red sandstone as well as limestone with beds of lime and shales (Swart 2008; Tordiffe 2010), which were formed around 530-550 million years ago (Tordiffe 2010).

The soils on the undulating to rolling landscapes are generally shallow, on bedrock, with a high skeletal content. These Leptosols have only a very limited water holding capacity, and can therefore only support limited vegetative growth. Along the river, sedimentary deposits by the river form Fluvisols, which are deeper, and potentially nutrient-richer (ICC *et al.* 2000; Mendelsohn *et al.* 2002).

Natural vegetation

Gibeon falls within the northern Nama-Karoo biome along the Fish River. This biome is characterised by open short shrubs and grasses which make up most of the perennial vegetation. Big trees are rare and are mostly limited to rivers (Irish 2008). Giess (1998) describes the vegetation as being dominated by *Parkinsonia africana*, *Rhigozum trichotomum* and a variety of other dwarf shrub species, whilst *Stipagrostis* species are dominating as grasses. Only limited detailed vegetation descriptions are available for the Dwarf shrub savanna at the Nico Nord observatories to the south-east, as well as the farm Haribes to the north of the study area (Jürgens *et al.* 2010; Strohbach & Jankowitz 2012). For the Fish River Valley, specifically the riparian forest at the Fish River, no descriptions are available.

Environmental challenges
Some challenges experienced in an arid environment like Gibeon, include overgrazing due to livestock (Kruger 2001), potentially leading to desertification. Secondary land degradation can also be caused by alien invasive species such as *Prosopis*, initially taking advantage of the disturbances. *Prosopis* however aggressively invades the area at the expense of native species, in this way transforming the habitat and reducing the plant species diversity (Bethune *et al.* 2004; van den Berg 2010). Within this arid environment, water scarcity due to low rainfall, is a recurring problem. This is aggravated by invasive *Prosopis* spp., which are known to extract excessive amounts of water from the soil, even reducing water flow (Le Maitre *et al.* 2000; Nie *et al.* 2012; Dzikiti *et al.* 2013).

Assessment methods

Biodiversity assessments
In order to assess the plant diversity, at each plot a relevé (i.e. a Braun-Blanquet type survey) was compiled following standards set for the Vegetation Survey of Namibia project (Strohbach 2001, 2014; Mueller-Dombois & Ellenberg 2002; Kent 2012). For this purpose, a 20 x 50 m plot was set out. The position of this plot was determined with a Garmin eTrex 20 GPS (set to WGS 84), the general landscape and habitat features were described and a photo was taken. Following this, all identifiable plant species were recorded. Herbarium specimens from unknown species were collected, for later identification in the National Herbarium of Namibia (WIND). For each recorded species, the typical growth form and an estimated canopy cover (as abundance measure) were recorded.

The relevés were captured in TurboVeg (Hennekens & Schaminée 2001), using the Namibian species list (Klaassen & Kwembeya 2013) as base. This data has been incorporated into the National Phytosociological database of Namibia (Dengler *et al.* 2011; Strohbach & Kangombe 2012) (AF-NA-001). The actual relevé data from these plots forms the basis for long-term monitoring of the biodiversity (Westfall & Greeff 1998; Strohbach 2012).

The relevé data was exported to Juice (Tichý 2002) and grouped with Modified TWINSPAN (Roleček *et al.* 2009). From these groups, a summary composition in the form of a synoptic table was obtained. At the same time, characteristic/dominant species for each habitat could be determined.

Mapping
Habitat types were mapped using aerial photographs from 2010 with a ground resolution of 0.5 m. Two images, 2517BA-15 and 2517BB-11 were used for this. Habitat types were identified by visual interpretation and manually digitised with QGIS Valmeira Edition (*QGIS* 2014). The study area was defined as the town of Gibeon, as well as the river-associated habitats along the Fish River adjacent to Gibeon, from ca 3 km upstream of Gibeon, to 5 km downstream up to the bridge across the Fish River. Although the vegetation of the fountain area is in composition similar to the riparian vegetation, these two were mapped separately due to the fact that these represent different ecosystems in the area. Once the mapping was completed, the area of each habitat type was calculated.

Density of Prosopis stands
In order to determine the density of *Prosopis* in the different habitats, a transect count over 4 x 100 m (i.e. 400 m^2) was done of all woody species at each plot, with the exception of the floodplain plots. Here, the density of *Prosopis* was found to be too low for effective counting on these transects. For the transect count, the trees and shrubs were counted per size classes as follows: 0 - 1 m; 1 - 2 m; 2 - 3 m; 3 - 4 m; 4 - 5 m; 5 - 8 m; > 8 m. This data was summarised as trees (> 3 m) and shrubs (< 3 m).

Estimated water use of *Prosopis*

Water use by trees is dependent on three factors: the tree species and its intrinsic capacity to utilize water, the total leaf area of the plant as well as the climate (daily temperature, wind speed, humidity, etc.) (Cable 1977; Levitt *et al.* 1995; Wullschleger *et al.* 1998). Levitt *et al.* (1995) developed a water use coefficient for *Prosopis alba* in Tucson, Arizona, under similar, if slightly cooler, climatic conditions as the present study area. Their coefficient is calculated as follows:

$$K_{trees} = T / ET_0 \qquad [1]$$

where T is the transpiration of the particular tree (in mm*day^{-1}) and ET_0 is the base evapotranspiration of the environment (in mm*day^{-1})

T for the particular species can be calculated either as a function of the total leaf area (TLA) or a function of the projected canopy area (PCA) as follows:

$$T_{TLA} = H_2O / TLA \qquad [2]$$

or

$$T_{PCA} = H_2O / PCA \qquad [3]$$

where H_2O refers to the measured water use in litres per day. Both T_{TLA} and T_{PCA} have units of mm*day^{-1}.

Based on these formulas, the water use per tree can be calculated as follows:

$$H_2O = TLA * ET_0 * K_{TLA} \qquad [4]$$

or

$$H_2O = PCA * ET_0 * K_{PCA} \qquad [5]$$

From personal observations it was clear that *Prosopis chilensis* represented at least 80% of the *Prosopis* population within the study area, with *P. velutina* and *P. glandulosa* (in sequence of importance) making up the remainder of the population. *P. chilensis* has a very similar growth form and similar leaf size to *Prosopis alba* (Pasiecznik *et al.* 2004). It is thus assumed, that water use coefficients for of the *Prosopis* population found in the current study area will be similar to the water use coefficient of *Prosopis alba*.

Crown dimensions, following BECVOL (Smit 1989a, 1989b, 2014), were measured for 56 sample trees. A linear regression was calculated between the crown diameter and the tree height (Figure 2) for these sample trees. This regression was used to calculate average crown diameters for the size classes used for determining the density of the *Prosopis* stands (Table 1) in this study, based on the mid points of these size classes.

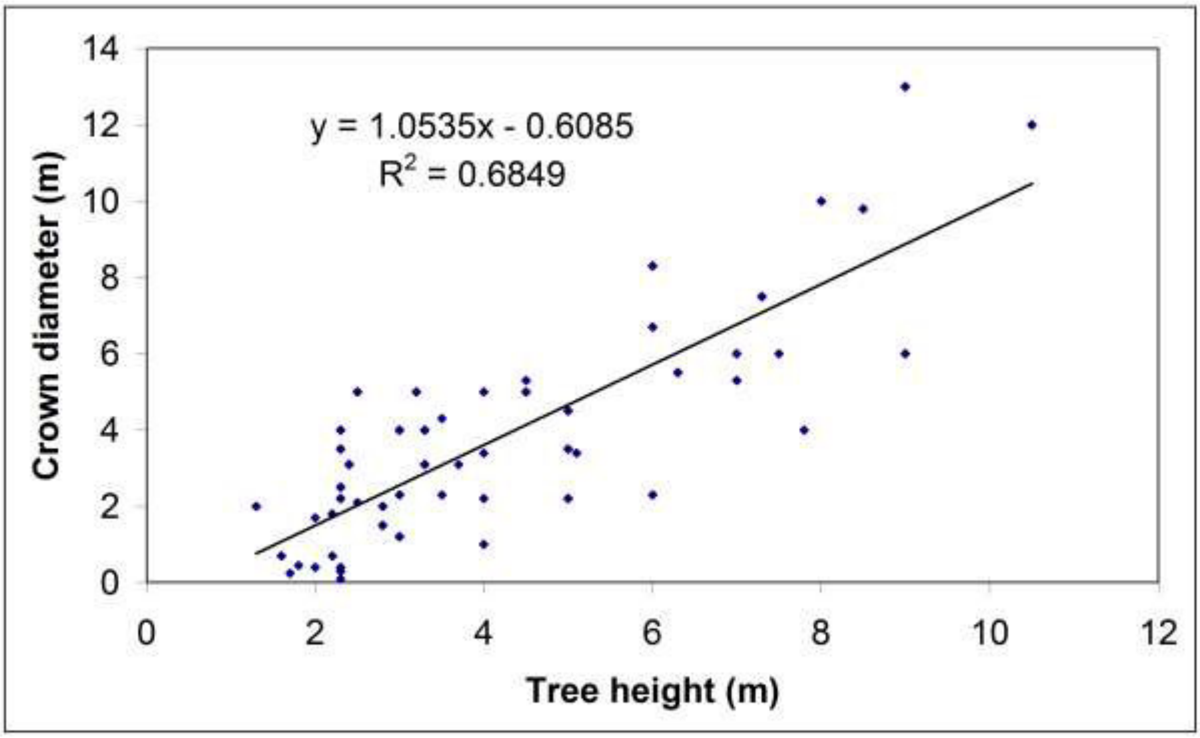

Figure 2. Relationship between tree height and crown diameter of 56 *Prosopis* trees measured for woody biomass determinations (Strohbach *et al.* in prep.).

Levitt *et al.* (1995) provide a range of PCA measurements for their sample trees, which were about 3 m tall. An average PCA of 0.4892 m^2 was calculated for these 3 m tall trees. Based on the relative differences of the crown diameter, the PCA was adjusted for each size class used in this study. Using formula [5] above, with K_{CPA} 1.56, as well as ET_0 at 9.589 mm*day^{-1} (derived from Mendelsohn *et al.* 2002), an estimated water use per tree per day could be calculated for these size classes (Table 1). With this estimated water usage per plant, the total estimated water usage could be extrapolated for each habitat, based on the density measurements.

Table 1. Projected crown area and estimated water usage for different size classes of *Prosopis* in the study area, based on data from Levitt *et al.* (1995).

Size class (m)	Size class midpoint (m)	Average crown diameter (m)	Relative crown diameter	Adjusted Projected Crown Area (m^2)	Estimated water use per plant per day (l)
0-1	0.7	0.129	0.051	0.025	0.379
1-2	1.5	0.972	0.381	0.186	2.857
2-3	2.5	2.025	0.794	0.388	5.954
	3*	2.552	1.000	0.489	7.503
3-4	3.5	3.079	1.206	0.590	9.052
4-5	4.5	4.132	1.619	0.792	12.149
5-8	6.5	6.239	2.445	1.196	18.343
> 8	9.5	9.400	3.683	1.802	27.635

* Standard size of trees measured by Levitt *et al.* (1995).

Results

Vegetation description

Twenty-five plots were sampled during the period 28 to 30 July 2014. A total of 60 species, representing 20 families and 47 genera were observed from the 25 relevés sampled. The Poaceae family was the most abundant with 17 species followed by the Fabaceae with eleven species and Asteraceae with seven species. Three species of *Prosopis*, being *P. chilensis*, *P. glandulosa* and *P. velutina* were recognised.

The classification of the relevés revealed three plant communities in the study area, being *Acacia nebrownii* shrublands within the upper slopes of the commonage, *Tetragonia schenkii* shrublands on the floodplains and finally the *Tamarix usneoides* woodlands along the river banks and in the fountain area. The detailed composition of these communities is presented in the form of a synoptic table in Table 2.

Table 2. Synoptic table showing the fidelity[1] as well as the average percentage cover of species occurring in the three plant communities.

	phi coefficient of fidelity			Average percentage cover		
Group No.	1	2	3	1	2	3
No. of relevés	4	5	16	4	5	16
Habitat	commonage	floodplains	riparian & fountain	commonage	floodplains	riparian & fountain
Acacia nebrownii	95.5	---	---	27.8	0	24
Melolobium species	81.6	---	---	0	0	0
Enneapogon desvauxii	79.5	---	---	0	0	0
Rhigozum trichotomum	63.2	---	---	0.3	0	0
Euphorbia species	63.2	---	---	0	0	0
Parkinsonia africana	63.2	---	---	1	0	0
Aristida adscensionis	60.8	---	---	8.8	1	1
Eragrostis nindensis	53.3	---	---	0	0	0
Tragus racemosus	---	100	---	0	0.6	0
Tetragonia schenkii	---	80.2	---	0	41.6	1.4
Schmidtia kalahariensis	---	75.3	---	0	0	0
Chloris virgata	---	59.2	---	0	0	0
Pechuel-Loeschea leubnitziae	---	55.5	---	0	0	0
Tamarix usneoides	---	---	81.6	0	0	16.3
Senecio windhoekensis	---	---	72.5	0	0	0.6
Acacia karroo	---	---	53.5	0	0	7.2
Stipagrostis hochstetteriana	---	---	---	0	0	0
Schkuhria pinnata	---	---	---	0	0	0
Stipagrostis uniplumis	---	---	---	0.3	0	0.1
Lycium species	---	---	---	0	0	3.5

[1] Fidelity refers to the degree a particular species is "true" to a particular community (i.e. occurring in all sample plots of a particular community, but not in sample plots belonging to other communities). The measure given is the phi coefficient of fidelity (Chytrý *et al.* 2002). Values from 60 and higher are regarded as highly diagnostic.

Eragrostis lehmanniana	---	---	---	0	0	0
Galenia papulosa	---	---	---	0	6.8	0.4
Cyperus marginatus	---	---	---	0	0	5
Forsskaolea species	---	---	---	0	0	0
Calicorema capitata	---	---	---	0	0	3
Chenopodium species	---	---	---	0	1	1
Enneapogon cenchroides	---	---	---	0.7	1.3	0.3
Flaveria bidentis	---	---	---	0	0	0.4
Acacia mellifera	---	---	---	3	0	0
Sesamum species	---	---	---	0	0	0
Stipagrostis namaquensis	---	---	---	0	0	3.5
Mesembryanthemum species	---	---	---	0	3.8	2.7
Stipagrostis obtusa	---	---	---	0	0	0
Lotononis platycarpa	---	---	---	0	0	0
Prosopis species	---	---	---	4	4	24.7
Senecio species	---	---	---	0	0	0
Zygophyllum simplex	---	---	---	0	0.3	2.6
Lycium eenii	---	---	---	1	0	4.2
Dicoma species	---	---	---	0	0	0
Dactyloctenium aegyptium	---	---	---	0	0	0
Cynodon dactylon	---	---	---	0	0.3	2.3
Acacia erioloba	---	---	---	0	0	10
Acacia erubescens	---	---	---	5	0	0
Blepharis species	---	---	---	0	0	0
Setaria verticillata	---	---	---	0	0	1.3
Euclea pseudebenus	---	---	---	0	0	7
Salsola kali	---	---	---	0	0	1.7
Jamesbrittenia canescens	---	---	---	0	0	0
Monechma species	---	---	---	0	0	0.7
Boscia foetida	---	---	---	1	0	1.7
Aizoon species	---	---	---	0	0	0
Suaeda species	---	---	---	0	0	12.5
Eragrostis trichophora	---	---	---	0	0.3	0.2
Cucumis species	---	---	---	0	0	0
Cleome species	---	---	---	0	0	0
Kleinia longiflora	---	---	---	0	0	1
Sericorema sericea	---	---	---	0	0	0
Datura inoxia	---	---	---	0	0	0
Eragrostis porosa	---	---	---	0	0.4	0.1
Gymnosporia senegalensis	---	---	---	0	0	0

1. Acacia nebrownii ***shrublands***

Four plots have been classified into this community, with a total of 23 species observed in these. The *Acacia nebrownii* shrublands are found on the high-lying outskirts of the settlement areas commonly referred to as "commonage" (Figure 3 and Table 2). The community is characterised by diagnostic deciduous shrubs and dwarf shrubs *Acacia nebrownii*, *Melolobium* sp., *Rhigozum trichotomum*, *Parkinsonia africana* and grasses *Aristida adscensionis*, *Enneapogon desvauxii* and *Eragrostis nindensis*. The habitat are rolling to moderately steep hill slopes, generally with shallow, stony soils on Dwyka shales (Geological Survey 1980). Although *Acacia nebrownii* also occurs in another plant community (i.e. *Tamarix* woodland) it is highly abundant in this shrubland. The leaves of *Acacia nebrownii* were browsed by livestock and it may be for this reason that the local people let it grow in abundance. The presence of *Aristida adscensionis* as dominant species, in addition to the relative high abundance of *Prosopis* spp. and *Acacia nebrownii*, is a sign of degradation and bush encroachment, replacing the more open dwarf shrubland dominated by *Enneapogon desvauxii, Eragrostis nindensis* and *Stipagrostis* spp*.,* which are known as subclimax and climax grasses in the area (Jürgens *et al.* 2010; Müller 2007).

Figure 3. An example of the *Acacia nebrownii* shrublands as found in the commonage between the houses and other town buildings.

2. *Tetragonia schenkii* shrublands

Eight plots have been classified into this community, with a total of 27 species having been observed in these. The *Tetragonia schenkii* shrublands are found in the flood plains of the Fish River with deep alluvial deposits. They are characterised by shrubs of endemic *Tetragonia schenkii* and the annual grasses *Chloris virgata*, *Tragus racemosus* and *Schmidtia kalahariensis* (Figure 4 and Table 2). These grass species are of low grazing value and are seen as indicators of poor veld conditions. They mainly grow in disturbed, overgrazed or bush encroached areas (Müller 2007). The community is dominated by *Tetragonia schenkii*, *Prosopis* spp., *Galenia papulosa* and *Mesembryanthemum* sp. These are, with the exception of *Prosopis* spp., all leaf-succulent species, giving the community a distinct succulent character, which is a sign that the water availability is limited and highly seasonal. *Prosopis* plants are only sparsely distributed within this plant community. Because of this, their density could not be adequately determined with the belt transect method.

Figure 4. The *Tetragonia schenkii* shrublands on the floodplains of the Fish River.

3. ***Tamarix usneoides*** **woodlands**

Thirteen plots have been classified into this community, with a total of 24 species having been observed here. The community is characterized by *Prosopis* spp., *Tamarix usneoides*, *Euclea pseudebenus*, *Acacia karroo*, *Acacia erioloba*, *Acacia nebrownii*, *Lycium eenii*, as well as *Zygophyllum simplex, Mesembryanthemum* sp. and *Senecio windhoekensis* as the main species for the herbaceous layer (Figure 5 and Table 2).

Figure 5. The vegetation on the river bank (top), the fountain habitats (middle), and the river beds (bottom) belong collectively to the *Tamarix usneoides* woodlands.

Although they did not vary much floristically, three different vegetation communities could be recognised in the field according to their habitat and structure, being the dense thickets along the fountain areas, the riparian woodlands on the river banks and the sparse vegetation of the river beds and floodplains subject to regular flooding and water flow.

Large parts of the fountain area have high salt contents in the soils. This, as well as shallow rocky soils, that makes the soil unfavourable for many woody species as well as for most grass. Due to the constant supply of spring water, though, *Prosopis* spp. flourishes in these areas. Another indicator of such constant water supply is *Cyperus marginatus*.

The riparian vegetation along the river banks do not differ significantly in composition or structure from the vegetation of the fountain area, with the exception of the more constant occurrence of *Euclea pseudebenus* and the fact that the vegetation is more dense. Some huge *Prosopis* trees*,* with a stem diameter of well over 1 m, were found here. These old trees are an indication that the infestation by this alien invasive could date back to the early 20th Century (this, however, could not be verified). The habitat is generally deep alluvial sands, with a shallow water table.

The river bed vegetation has a similar composition to the previous two communities, but due to the fact that these are subjected to flowing water at least once per year, is comparatively sparse, especially with the number of *Prosopis* being conspicuously low.

Because of the differences in habitat, and also differences in structure and density, these three sub-communities are treated separately in the subsequent discussion.

Biodiversity of the plant communities

Comparing the species diversity of the different plant communities, it becomes clear that the open properties within the town of Gibeon (the "commonage") as well as the fountain thickets support the highest species richness, with the river bed vegetation having the lowest richness. The floodplain vegetation has a very uniform species composition (dominated by *Tetragonia schenkii*), whilst the river banks are highly variable in species richness. This could be due to these areas having a considerable environmental variability from close- to further away from the river (Figure 6a).

The Simpson's diversity index (a dominance index) tells a different story: The river bed vegetation show a comparatively high variability, compared to the diversity of the riparian thickets (Figure 6b). The riparian thickets are relatively uniform in their diversity, indicating a high level of dominance (by *Prosopis* spp.) in this community. Also the fountain area shows a generally high level of dominance, but with higher variability. This is borne out by the density of trees, in particular *Prosopis* spp.: roughly half of the tree cover within the riparian, fountain and river bed vegetation is provided by this alien invasive, severally limiting the growth of other species (Figure 7). The woody cover in the river bed area is obviously relatively low. A number of large *Acacia karroo* trees were observed to be dead in the fountain and riparian communities, whilst even large *Acacia erioloba* trees showed signs of reduced growth due to the severe competition by *Prosopis* trees and shrubs for water and growing space (Figure 8). Other typical riparian species like *Ziziphus mucronata* and *Euclea pseudebenus* were observed as juvenile plants, but very seldom as large trees or shrubs. Only the weedy *Acacia nebrownii*, a relative small shrub, seemed to thrive here, albeit at far lower densities than in the commonages. The population of *Prosopis* at Gibeon is strongly dominated by the smaller trees and shrubs (< 3 m) (Table 3), indicating a strongly regenerating/expanding population.

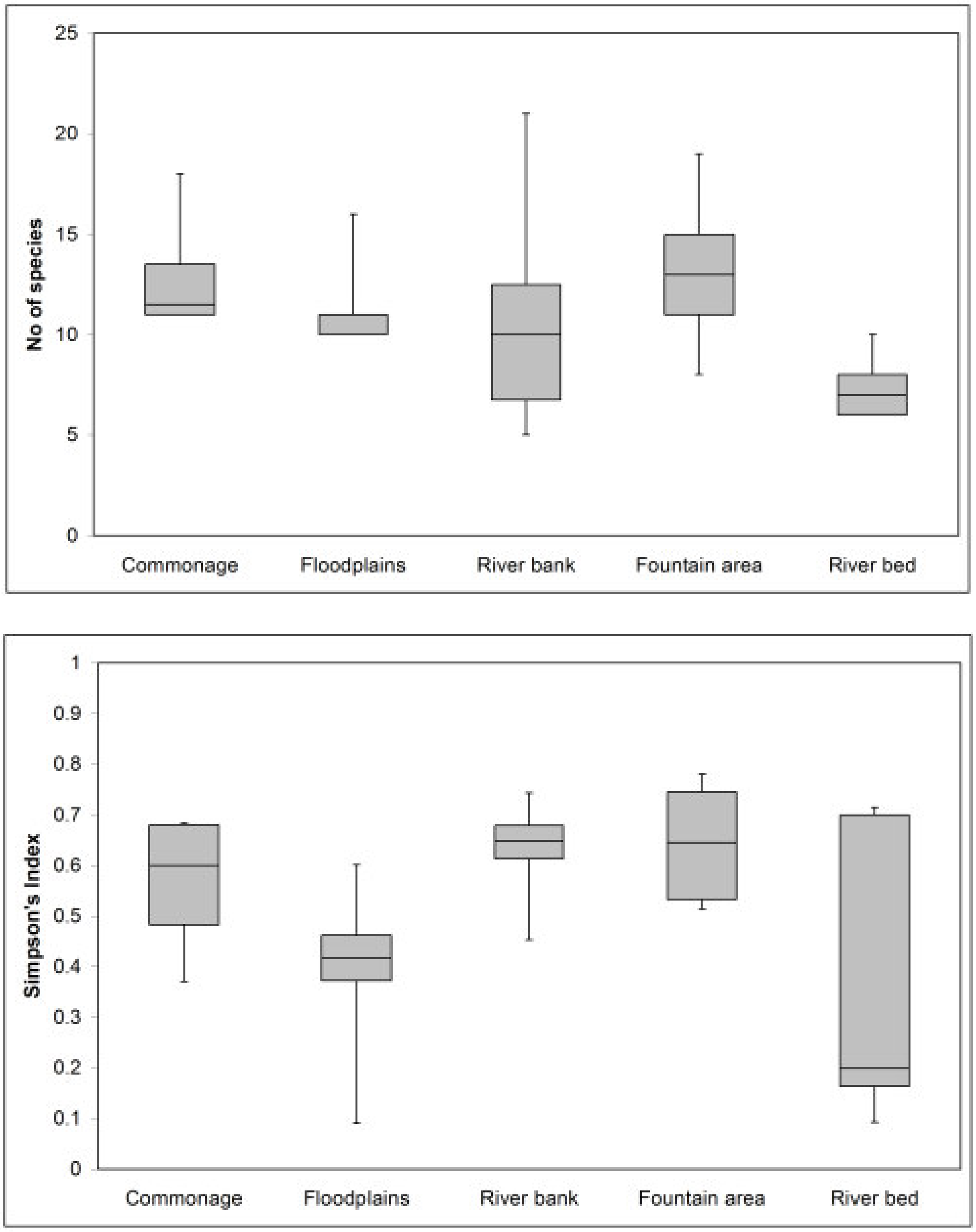

Figure 6. Box-and-whisker plots of the species richness of the various communities (top); Box-and-whisker plots of Simpson's Diversity Index of the individual plots within each community (bottom).

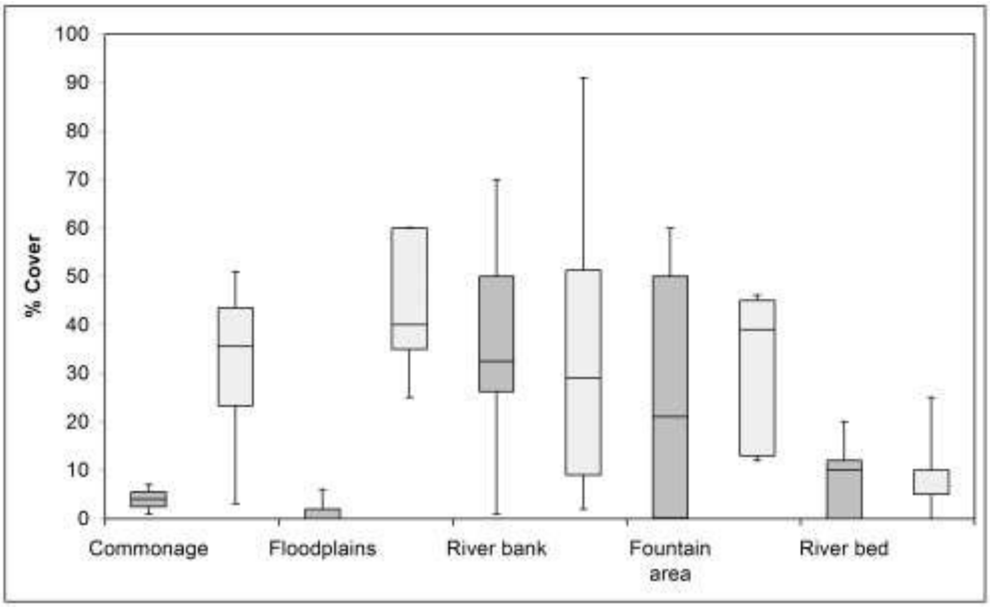

Figure 7. Percentage canopy cover of *Prosopis* spp. (dark grey/left boxes) and in relation to it, by indigenous woody species (light grey/right boxes), in the various plant communities.

Figure 8. Large *Acacia erioloba* tree within the fountain vegetation with strongly reduced foliage, indicating severe hardship due to competition from *Prosopis* stands surrounding it.

Table 3. Area of different vegetation types within the Gibeon study area, with approximate tree and shrub densities.

Landscape	Area (ha)	*Prosopis* shrub density	*Prosopis* tree density	Other shrub species	Other tree species
	(Total area: 678.47 ha)	(plants/ha)		(plants/ha)	
Commonage	142.35	470	25	106	0
Floodplains	277.03	No data		No data	
Fountain vegetation	44.30	925	144	279	8
River bank vegetation	113.45	2510	425	422	75
Riverbed	101.35	125	58	417	0

Mapping

The habitat map is shown in Figure 9, and the area covered by each habitat within the study area in Table 3.

The town of Gibeon has considerable "brown space", i.e. unoccupied erven amongst its houses. Especially in the western part of the town, a fair amount of *Prosopis* shrubs (very few trees) were observed in this 'brown space'. This could be due to the spreading of seeds through humans and livestock alike, taking advantage of an already degraded environment. A particular large piece, south along the main road (ca 92 ha), did not show much of a *Prosopis* infestation, except for the road verges (and from the aerial photographs, adjacent to the old sewage plant).

Considering that tree removal has to be undertaken for effective control, and harvesting of wood is a definite option, cognisance has to be taken of limitations by the Forestry Act (Government of Namibia, Act 12 of 2001). This dictates that no felling of trees may take place within a 100 m strip of the river bank. For this purpose a 100 m buffer zone was demarcated around the actual river bed. The 100 m buffer zone surrounding the Fish River covers about a third of the riparian vegetation. This area is also the densest *Prosopis* population (due to proximity to the river).

Estimated water use by *Prosopis* in the study area

The estimated water use for a single, 3 m high *Prosopis* tree of 7.5 l/day for the Gibeon area (Table 1) is within range of the measured water use of a 3 m high *Prosopis alba* tree in Arizona (up to 5.5 l/day) (Levitt *et al.* 1995). The difference can likely be attributed to a harsher climate at Gibeon, as reflected by the high rates of evaporation. The projected water use, based on the density data of *Prosopis* spp. within each habitat, is presented in Table 4.

Table 4. Estimated water use by *Prosopis* plants within the different habitats.

	Area (ha)	Water use by *Prosopis*		
		l per day per ha	total m^3 per day	total m^3 per year
Commonage	142.35	1,216.2	173.1	63,192.9
Floodplains	277.03	No data		
River bank	44.30	34,273.8	1,518.3	554,189.5
Fountain area	113.45	5,599.5	635.3	231.869.0
River bed	101.35	10,286.9	1,042.6	380,592.0
Totals	678.47	51,376.4	3,369.3	1,229,793.4

Levitt *et al.* (1995) indicated that the water use co-efficiency of *Prosopis* based on the projected crown area (K_{PCA}) is less reliable than K_{TLA}. However, no suitable measurements to calculate water use based on K_{TLA} were made in the field. Thus an intrinsic error can be assumed to the above calculations. Should this work ever be repeated or improved on, it will make sense to both recalibrate the TLA for the *Prosopis* species in Namibia, as well as measure the evapotranspiration rates of these species to obtain an improved K_{TLA} value.

Discussion and Conclusion

Ecological implications of *Prosopis* encroachment

The highest density of *Prosopis* spp. in comparison to other woody species is found in the riparian habitat along the Fish River at Gibeon. This alien invasive has significantly replaced the natural vegetation in the area. Virtually no knowledge is available on the original vegetation of the central Fish River. However, for the Farm Haribes the vegetation along the Lewer River is described by Strohbach & Jankowitz (2012) as short open woodland dominated by *Ziziphus mucronata*, with a well-developed understorey of shrubs and grasses. In comparison, the river banks at Gibeon had virtually no herbaceous understorey (Figure 5a); whilst the typical river species were either only present as seedlings or saplings (*Ziziphus mucronata*) or as stunted or dead remains of trees (*Acacia karroo*). Even deep-rooted species like *Acacia erioloba* (Canadell *et al.* 1996; Moustakas *et al.* 2006) are severely affected by the competition with *Prosopis* plants (Figure 8). *Prosopis* is also known to be allelopathic (Noor *et al.* 1995), thus preventing seedlings of other species to establish. Only *Tamarix usneoides* seems able to withstand the encroachment by these invasive species reasonably.

The negative impact of *Prosopis* on natural vegetation is supported by Wise *et al.* (2012) and Shackleton *et al.* (2015) who reported that in South Africa stands of *Acacia erioloba* died as a direct result of *Prosopis* invasions that lowered the water table. Auala *et al.* (2012) indicated that *Acacia erioloba* (both seedlings and large trees) were found in areas in the Auob Basin where *Prosopis* was cleared out compared to areas where *Prosopis* was not cleared.

Being a phreatophyte, *Prosopis* is known to use an immense amount of water, more than many other species (Le Maitre *et al.* 2002; Huxman *et al.* 2005). Its root system allows it to efficiently utilise both surface and ground water to depths of >50 m (Wise *et al.* 2012; Shackleton *et al.* 2015). To put the water use of *Prosopis* into perspective, the following two examples are given:

(i) The total annual water use of the City of Windhoek is about 22.6 M m^3 (Uhlendahl *et al.* 2010) The total annual water use of *Prosopis* at the study area (1.2 M m^3)

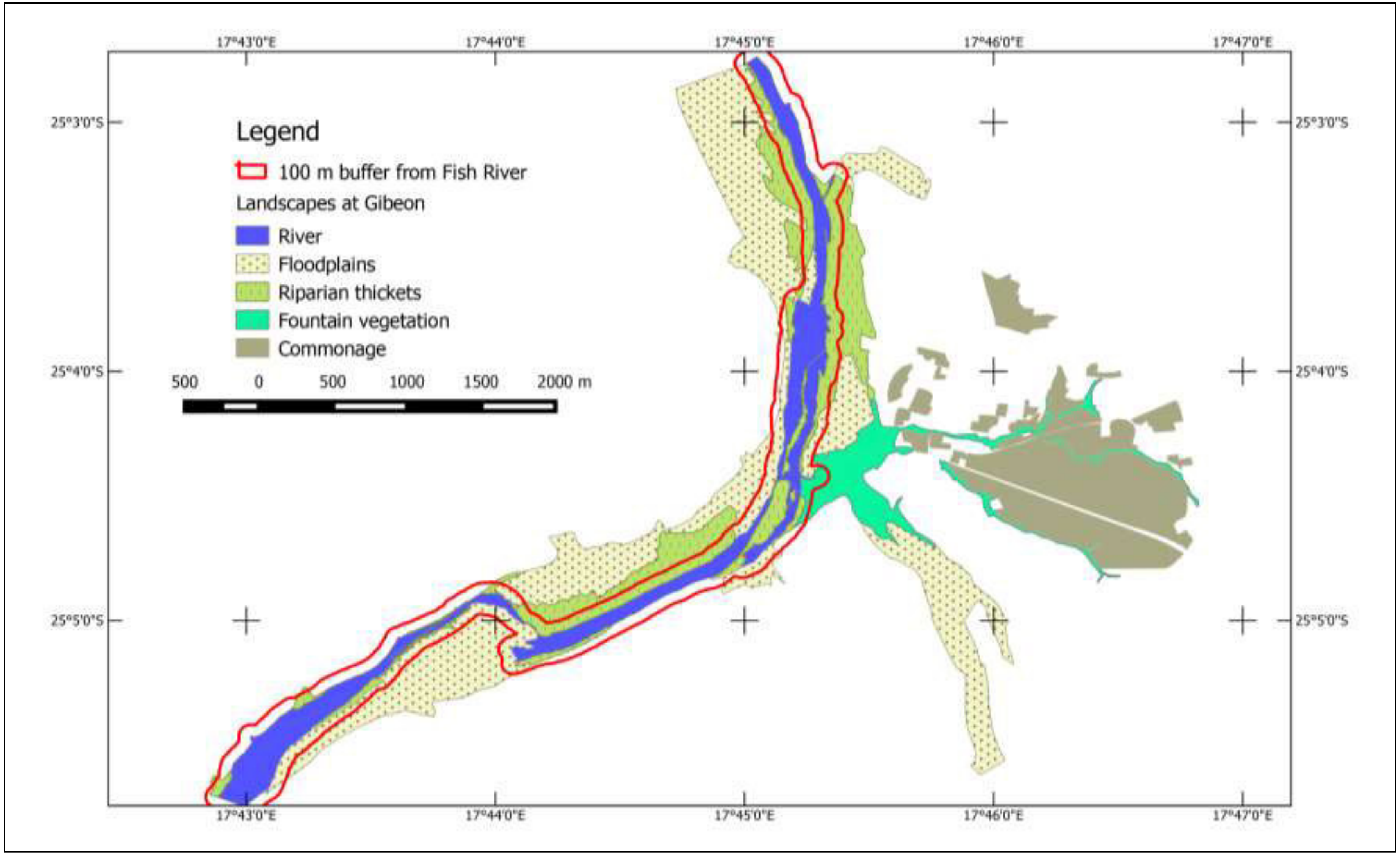

Figure 9. Habitat map of the Fish River valley areas around the town of Gibeon.

The unmapped areas in most cases represent the rolling Nama-Karoo landscape of southern Namibia surrounding Gibeon. The red outline represents the 100 m wide buffer area dictated by the Forestry Act.

(i) represents 5.4% of this. This translates to a five times higher water consumption per unit area than Windhoek.

(ii) Natural vegetation along the Kuiseb River has been measured to use 202,000 m^3 per annum per 1 km stretch or river (Bate & Walker 1993). This vegetation consists of a mixture of *Acacia erioloba, Faidherbia albida, Euclea pseudebenus* and *Tamarix usneoides*. We can assume that the original vegetation of the Fish River bank had a similar composition, with the exception that *Faidherbia albida* would be replaced by *Acacia karroo*. The river meanders over roughly 320 km between the Hardap Dam and the new Neckartal Dam. If natural vegetation with similar water use as in the Kuiseb River would prevail, it would use roughly 64.7 M m^3 per annum. However, a 100 m wide strip of *Prosopis*-infested vegetation next to the same distance of the river would use 219.4 M m^3 per annum – a difference of 154.8 M m^3 per annum more than natural vegetation. This difference presents 18.1 % of the projected capacity of the Neckartal Dam (857 M m^3) (Salini Impregilo 2013).

In addition, *Prosopis* is known to increase rapidly: the population expands at 18% per annum, resulting in the invaded area to double every five years (Smit 2005). Therefore, if the infestation of *Prosopis* along the Fish River is not managed, the situation will likely exacerbate and *Prosopis* invasions may alter the hydrology of the Fish River. This could have major impacts on the new Neckartal Dam development.

The obvious choice for the management will be harvesting of trees, but must also include the removal of saplings (no harvestable woody biomass). In collaboration with the Directory of Forestry, a way needs to be devised how to reduce the number of *Prosopis* trees along the river bank within the 100 m buffer zone, without endangering this bank through erosion during flash floods.

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