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Review

50 years of water extraction in the Pampa del Tamarugal basin: Can *Prosopis tamarugo* trees survive in the hyper-arid Atacama Desert (Northern Chile)?

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ABSTRACT

Groundwater-dependent ecosystems are threatened worldwide by unsustainable groundwater (GW) extraction. This is the case of the *Prosopis tamarugo* Phil forest in the hyper-arid Atacama Desert (Northern Chile), one of the most extreme ecosystems on Earth. Despite concerns about the conservation of this ecosystem, little research has been done to quantify the effects of the increasing GW depth (GWD) on the Tamarugo population. Here we provide a spatio-temporal assessment of the water condition of Tamarugo trees and propose GWD thresholds for their conservation. We studied spatio-temporal changes of GWD and the water status of the forest using Landsat images and hydrogeological records (1988–2013). This was complemented with a digital inventory and estimation of the green canopy fraction (GCF) of all trees using fine resolution satellite images. Since Tamarugos are solar trackers, their canopy spectral reflectance changes on a diurnal and seasonal basis. Thus, novel remote sensing drought stress indicators were defined: the mean NDVI in winter ($NDVI_W$) accounting for foliage loss and the NDVI difference between mean winter and summer ($\Delta NDVI_{W-S}$) accounting for canopy water loss. $NDVI_W$ and $\Delta NDVI_{W-S}$ of the Tamarugo forest declined on average 19% and 51%, respectively, while GW depleted on average 3 m over the period 1988–2013. About 730,000 trees were identified in the study area, from which 5.2% showed a GCF < 0.25 associated with severe drought stress. A GWD > 12 m increasingly limited the paraheliotropic leaf movement, leading to dehydration and foliage loss. Tamarugos at 12–16 m GWD suffered moderate drought stress while GWD of 16–20 m implied severe drought stress. We suggest 20 m GWD as a critical threshold for the survival of Tamarugo trees.

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1. Introduction

Water is a limiting resource for wildlife and human activities in arid and semi-arid areas. As national economies develop, the pressure for using the scarce water sources of desert basins to provide water to urban centers and industry increases, becoming a threat for desert ecosystems worldwide (Eamus et al., 2015; Ezcurra, 2006; Pringle, 2001). The main water source in deserts is the groundwater (GW) and several authors have highlighted the importance of assessing the negative impacts of GW extraction on natural vegetation (Elmore et al., 2006; Naumburg et al., 2005; Patten et al., 2008). Desert vegetation provides important ecosystem services such as the regulation of the hydrological cycle, the conservation of endemic and rare species, and the provision of an oasis for local settlements, grazing and small scale agriculture (Ezcurra, 2006). The expected decrease in available fresh surface water due to global warming together with the future increase of water consumption at global scale, make GW overexploitation likely to occur (Wang et al., 2014). As a result, the main challenge for water managers today is to promote a sustainable exploitation of GW aquifers compatible with the conservation of desert ecosystems (Elmore et al., 2003). Chilean environmental institutions are already facing such a challenge in the Pampa del Tamarugal aquifer, where one of the most extreme desert ecosystems still remains in the heart of the Atacama Desert (Northern Chile).

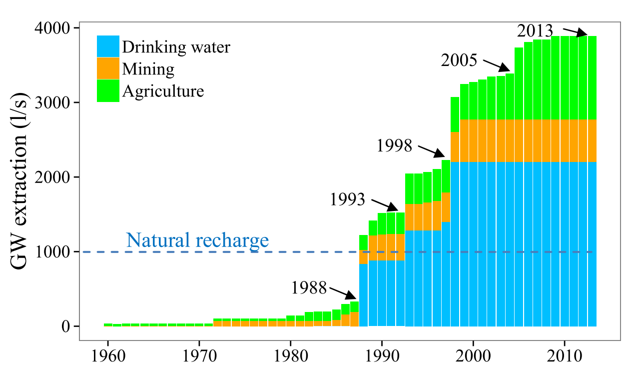

Fig. 1. Legally authorized groundwater extraction and estimated natural recharge for the Pampa del Tamarugal aquifer in the period 1960–2013.
Source: DGA, 2011.

The Pampa del Tamarugal aquifer is the only source of drinking water for a large area in the Atacama Desert and for more than 50 years GW has been extracted to supply water to urban areas (including important cities like Iquique), the mining industry and agriculture (Fig. 1). From 1988 onwards the authorized GW extractions have exceeded the natural recharge of the aquifer inducing GW depletion in the whole aquifer (Rojas and Dassargues, 2007). This unbalance in the water budget is threatening the Tamarugo *Prosopis tamarugo* Phil. trees, which are completely dependent on GW and limited to the areas with shallow GW. The main species of this ecosystem is the Tamarugo tree: an endemic tree species of the Atacama Desert. The 'Pampa del Tamarugal' formation provides habitat to about 40 other plant and animal species, some of them endangered and/or endemic species (CONAMA, 2008; Estades and López-Calleja, 1995; Ramírez-Leyton and Pincheira-Donoso, 2005). Currently, most of the Tamarugo ecosystem is under protection in the Pampa del Tamarugal National Reserve, administrated by the Chilean Forest Service (CONAF), but the question is whether CONAF can protect this ecosystem from the impact of GW extraction occurring in the whole aquifer.

Considering the cumulated GW depletion after 50 years of extractions, the Chilean Water Service DGA officially declared the Pampa del Tamarugal aquifer as 'restricted area' (Res. DGA Number 245) in 2009. Hence, no new GW extraction will be authorized from 2009 onwards. Although this is a positive action towards the conservation of the Tamarugo ecosystem, still the question remains whether this restraint is enough to consider the Tamarugo trees as safe in the future. There is consensus among environmental authorities on the decline of the Tamarugo trees due to GW depletion. However, there is a lack of studies quantifying the magnitude and extent of the impacts on the water status of the trees. Furthermore, there is no clear definition of a groundwater depth (GWD) threshold under which the water status of Tamarugo trees can be considered as unhealthy. These three aspects: the magnitude of the impacts, the extent and the thresholds for Tamarugo's survival are required for environmental impact assessment and water management. In this paper, we attempt to approach these aspects by analysing different remote sensing datasets and hydrogeological data.

Although previous studies have shown the usefulness of remote sensing for assessing water stress of Tamarugo (Chávez et al., 2013a, 2013i, 2014), these findings have not yet been applied on a large