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Title: Can management of 'thirsty' alien trees improve water security in semi-arid India?

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Keywords: Dryland; alien invasive plants; evapotranspiration; water management; ecosystem services; neem

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Abstract: Arid and semi-arid regions of central India receive scarce and episodic precipitation during the short monsoon season, and also experience substantial evaporation. Traditional and innovative water harvesting and governance practices improve water stewardship, or abate some impacts of intensive mechanised water extraction. However, significant numbers of alien trees, in particular Eucalyptus species with high water demands, populate some regions practicing progressive water stewardship. The water demands of these trees can potentially undermine efforts to achieve water security. Through interviews with community leaders in Indian villages with differing eucalyptus tree densities, water loss through evapotranspiration compared with livelihood demands was approximated. Literature review of the water demands and ecosystem services provided respectively by alien eucalypts and native, culturally valued neem trees supports assessment of the likely benefits and acceptability of a replacement programme favouring native trees. Although data limitations mean that the findings of this study are necessarily uncertain, they nonetheless illustrate the likely scale of impact, substantiating the case for alien tree management as an important contribution to water security. Alien vegetation management practices as a contribution to water security are already firmly established in South Africa, and are likely to yield equivalent benefits if translated to dryland India.

Response to Reviewers: See the detailed 'Response to Reviewers' attachment.

Can management of 'thirsty' alien trees improve water security in semi-arid India?

Dr Mark Everard, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK (E: mark.everard@uwe.ac.uk; M: +44-(0)-7747-120019).

Abstract

Arid and semi-arid regions of central India receive scarce and episodic precipitation during the short monsoon season, and also experience substantial evaporation. Traditional and innovative water harvesting and governance practices improve water stewardship, or abate some impacts of intensive mechanised water extraction. However, significant numbers of alien trees, in particular *Eucalyptus* species with high water demands, populate some regions practicing progressive water stewardship. The water demands of these trees can potentially undermine efforts to achieve water security. Through interviews with community leaders in Indian villages with differing eucalyptus tree densities, water loss through evapotranspiration compared with livelihood demands was approximated. Literature review of the water demands and ecosystem services provided respectively by alien eucalypts and native, culturally valued neem trees supports assessment of the likely benefits and acceptability of a replacement programme favouring native trees. Although data limitations mean that the findings of this study are necessarily uncertain, they nonetheless illustrate the likely scale of impact, substantiating the case for alien tree management as an important contribution to water security. Alien vegetation management practices as a contribution to water security are already firmly established in South Africa, and are likely to yield equivalent benefits if translated to dryland India.

Key words

Dryland; alien invasive plants; evapotranspiration; water management; ecosystem services; neem

STOTEN-D-19-13835R1: Can management of 'thirsty' alien trees improve water security in semi-arid India?

Response to reviewers and editor

Introduction

Many thanks for this review and the request for MINOR revisions to be made.

I am duly resubmitting both track-changed and a ‘clean’ revised manuscripts in MS Word.

All comments are reproduced below in black font.

- My responses to each of them are interleaved as bullet point in purple font

Comments from Reviewer #1

Dear Authors, I have seen now you have made many different corrections and changes, which let me to consider your manuscript again for pubication. Thanks for all the work done.

- Thank you for your thanks and acknowledgement of the revisions achieved!

The only thing that worries me is about the figures format. For example and as far as I know from the journal rules, horizontal lines have to be removed and the format of all figures should be the same along the manuscript. Please check it.

- Checking on https://www.elsevier.com/journals/science-of-the-total-environment/0048-9697/guide-for-authors, I cannot see any stipulation about figure formats that they should not have horizontal lines.
- There are five figures in all: (1) map [without horizontal lines]; (2) histogram derived from Excel graphical representation; (3) (4) and (5) graphs derived from Excel graphical representations. Aside from the map (1) obviously differing from the graphs (2-5) in format, I struggle to see any inconsistency.
- Does this comment in fact refer to Tables? There is just one Table. I note from https://www.elsevier.com/journals/science-of-the-total-environment/0048-9697/guide-for-authors that there is a requirement to “Avoid vertical rules” (not horizontal rules), so I have made that change in the resubmitted files.

Comments from Reviewer #3

This study discusses the benefits of replacing alien eucalyptus plantations by valued native species counterparts in dry areas of India, with the purpose to improve groundwater resources. This is not only a scientific but also a social issue and therefore the study was based on interviews to assess the adherence of local populations to this possibility.

- Thanks you, this is a fair summation of what was attempted and hence the mixed methods used.

The study underwent a first round of revision that resulted in noticeable improvements to the original version. The revised version is mostly Ok.

- Good, albeit that ‘mostly’ is noted… I respond to subsequent comments below.

I just have a comment on the Introduction. I am afraid that this section is too focused in the Indian case. It could be more ample in its scope. The problem addressed in this study is not exclusive from India and therefore the authors should expand the state of the art summary this regard, which would attract the interest to a wider audience.

- A fair statement, and one I have addressed taking account of the reviewer's points below.

For example,
- Line 40 "A diversity of innovations for harvesting and storage of seasonal run-off...". The authors should in a first instance broad the scope to recent innovations worldwide and then downscale the focus to the studied case. Otherwise the paper has limited interest to a n international readership. In that context, it can be referred recent studies on improved GIS based approaches to identify optimal rainwater harvesting systems (Terêncio et al., 2017, 2018) or public water supply systems based on conjunctive (surface and groundwater) water resources management (Soares et al., 2019), which could be acknlowledged to improve the revised version.

- Many thanks to the reviewer for supplying the three references, two of them now incorporated into the Introduction as suggested. I have included all three as footnotes[1] here so that they remain visible.
- However, I decided not to use the Terêncio (2018) reference, despite it being a STOTEN paper, as the 2017 reference suffices for the indicated purpose. Also, so that the paper has wider global spread, as suggested by the referee, rather than being 'India and Portugal-centric'… I have instead included new and relevant references to refer to groundwater recharge practices in Middle Eastern and North African countries (Salameh *et al*., 2019), in the Central Plateau region of Burkina Faso (Government of Burkina Faso, 2018) and the Ayacucho region of Peru (Ministerio de Agricultura y Riego, n.d.).
- This 'snapshot global perspective' in included as a new paragraph following that indicated by the reviewer.
- To emphasis the global transferability of this study, with appropriate adjustment, the following sentence has been added to the end of the Introduction: "Findings are transferrable, with regional geographical and cultural adaptation, to other global arid and semi-arid regions facing similar challenges" (lines 121-123 of the Word file).
- At the end of the paper, I again emphasise wider global relevance by inserting a new concluding paragraph of the Discussion "These findings have generic relevance if adapted to the differing geographical and cultural contexts of other global arid and semi-arid settings facing linked threats of water shortage and alien tree invasion. The problem and its associated solutions are well-established in South Africa, evidenced by the Working for Water programme and its underpinning science base. However, as exemplified by the negative impacts of alien tree invasions on stream baseflow in north-central Portugal (Hawtree et al., 2015) and the depression of vulnerable groundwater resources in Pacific islands (Meyer et al., 2011), these linked issues may be more globally pervasive, potentially under-researched and inadequately integrated within policy responses".

Further notes for the editor

[1] Terêncio, D.P.S., Sanches Fernandes, L.F., Cortes, R.M.V., Pacheco, F.A. L. (2017). Improved framework model to allocate optimal rainwater harvesting sites in small watersheds for agro-forestry uses. Journal of Hydrology 550, 318-330.
Terêncio, D.P.S., Sanches Fernandes, L.F., Cortes, R.M.V., Moura, J.P., Pacheco, F.A. L., 2018. Rainwater harvesting in catchments for agro-forestry uses: A study focused on the balance between sustainability values and storage capacity. Science of Total Environment 613-614, 1079-1092.
Soares, S., Terêncio, D.P.S., Sanches Fernandes, L.F., Machado, J., Pacheco, F.A.L., 2019. The Potential of Small Dams for Conjunctive Water Management in Rural Municipalities. Int. J. Environ. Res. Public Health 16, 1239.

As the body of the paper was deliberately kept relatively small to retain focus on the central narrative – supported by three Supplementary Material documents for those wishing to access further detail – there has been plenty of headroom to accommodate these additions and changes without breaching word count limits.

RRC-EA (In press) still remains 'in press' at this time, though the authors have returned final comments to the RRC-EA. RRC-EA have acknowledged and are typesetting in preparation for publication on the website. I anticipate that this reference will have a publication date by proofing stage.

Data in Brief (optional)

Ideally, I'd have converted the 'Supplementary Material' into a 'Data in Brief' contribution as suggested in the email from STOTEN requesting MINOR revisions. But, sadly, I have no funds for APC – a requisite for 'Data in Brief' – so cannot achieve this.

End of response to reviewers

Can management of 'thirsty' alien trees improve water security in semi-arid India?

Dr Mark Everard, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK (E: mark.everard@uwe.ac.uk; M: +44-(0)-7747-120019).

Abstract

Arid and semi-arid regions of central India receive scarce and episodic precipitation during the short monsoon season, and also experience substantial evaporation. Traditional and innovative water harvesting and governance practices improve water stewardship, or abate some impacts of intensive mechanised water extraction. However, significant numbers of alien trees, in particular *Eucalyptus* species with high water demands, populate some regions practicing progressive water stewardship. The water demands of these trees can potentially undermine efforts to achieve water security. Through interviews with community leaders in Indian villages with differing eucalyptus tree densities, water loss through evapotranspiration compared with livelihood demands was approximated. Literature review of the water demands and ecosystem services provided respectively by alien eucalypts and native, culturally valued neem trees supports assessment of the likely benefits and acceptability of a replacement programme favouring native trees. Although data limitations mean that the findings of this study are necessarily uncertain, they nonetheless illustrate the likely scale of impact, substantiating the case for alien tree management as an important contribution to water security. Alien vegetation management practices as a contribution to water security are already firmly established in South Africa, and are likely to yield equivalent benefits if translated to dryland India.

Key words

Dryland; alien invasive plants; evapotranspiration; water management; ecosystem services; neem

Introduction

India spans a diversity of climates and microclimates, from arid desert to the north-west to glaciers and alpine tundra in the Himalayan uplands and humid tropics in the south-west coast and island territories. The drier lands range from the fully arid Thar Desert, spanning approximately half of the state of Rajasthan and much of Gujarat, towards semi-arid regions receiving scarce rainfall extending westwards across the rest of Rajasthan and into northern Madhya Pradesh, Haryana and regions of adjacent states. The pronounced seasonality of rainfall predominantly during a short monsoon season, associated with high evaporation rates throughout the year, result in substantial dependence on groundwater for domestic, agricultural and other uses. Water scarcity is a pressing issue for both rural and urban livelihoods. Analysis of satellite gravity data indicates that current groundwater abstraction from the transboundary Indo-Gangetic Basin, comprising 25% of global groundwater withdrawals used to sustain~~ing~~ agriculture in Pakistan, India, Nepal and Bangladesh, is unsustainable but also compromised by extensive contamination (MacDonald *et al*., 2016).

A diversity of innovations for harvesting and storage of seasonal run-off, promoting aquifer recharge, are found across the region representing centuries of geographically and culturally adapted traditional knowledge adapting to local geographic and socio-economic conditions as well as historic changes in climate (Pandey *et al*., 2003; Gunnell and Krishnamurthy, 2003). However, intensive, mechanised water management solutions, such as tube wells and dam-and-transfer schemes, have led to a decline in traditional, community-based stewardship and, consequently, declining water security, compounded by centralised government control, economic pressures and climate change (Everard, 2015). Running counter to this trend has been a diversity of regional initiatives to reinstate locally adapted water harvesting and stewardship, especially in southern and western India (Bhanja *et al*., 2017). These initiatives, together with promotion of water efficiency measures, has seen some aquifer recovery (Van Meter *et al*., 2016; Bhanja *et al*., 2017).

Similar challenges, allied with renewed interest in groundwater recharge as part of a solution, are observed in other dryland regions globally. In Europe, seasonal deficits at village level in Portugal are observed as holiday-related rises in population coincide with the dry season, potentially compounded in future by climate change, leading to proposals for conjunctive water management based on surface water stored in small dams and groundwater (Soares *et al*., 2019). Terêncio *et al.* (2017) use a Multi Criteria Analysis (MCA) approach based on a Geographic Information System (GIS) to improve identification of optimal implementation of rainwater harvesting systems in this situation. Illustrative of wider groundwater recharge practices in Middle Eastern and North African countries, Salameh *et al*. (2019) review case studies in Jordan to assess conditions for the successful implementation of managed aquifer recharge. In west Africa, the Burkinabé Government now recognises and is seeking to promote the value and integration of nature-based solutions (NBS) and engineered infrastructure for water management in the Central Plateau of Burkina Faso (Government of Burkina Faso, 2018). In South America, promotion of local nature-based solutions for water storage and infiltration are being promoted by Peru's national government in the Ayacucho region to improve rural livelihood expectations, increase recharge capacities for reservoirs serving urban needs and address susceptibility to climate change in this semi-arid upland ecosystem (Ministerio de Agricultura y Riego, n.d.).

In dryland India, s~~S~~ome ~~dryland~~ regions in which progress is being made with water stewardship nevertheless contain significant numbers of alien tree species with high water demands. Particular concern has been expressed about the potential for alien *Eucalyptus* plantations to undermine community efforts to achieve water security (Srinivasan *et al*., 2015). Of India's estimated 45,000 plant species (Ali, 1999), roughly 40% are alien and, of this, approximately 25% are considered

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invasive alien plants (IAPs) (Raghubanshi *et al*., 2005). Significant amongst these alien trees are eucalypts (various large tree species of the genus *Eucalyptus* particularly including their hybrids). Eucalypts, native to Australia, were first planted in India on the Nandi Hills near Bangalore around 1790 by Tippu Sultan, ruler of Mysore (Shyam Sundar, 1984). By 1988, over 1,000,000 ha of eucalypt plantations had been established across India, by majority resulting from activities of State Forest Departments and Forest Development Corporations, with a further 6,000 million seedlings planted in private lands (Sandhu *et al*., 1988). The intent behind promotion of widespread eucalypt plantations was to convert natural forests of low perceived value to improve timber productivity and generate government revenue, with economic considerations narrowly focused on yield of timber including pulpwood (Mathur *et al*., 1984). Further reasons for the planting of eucalyptus, particularly hybrids, was as a means to counter the serious problem of waterlogging and secondary soil salinization in canal-irrigated arid and semi-arid regions (Ram *et al*., 2011).

The alien status of eucalyptus in India was one of many factors resulting a study by the FAO (UN Food and Agriculture Organization) on the benefits of plantations, taking into account wider ecological, economic, hydrological and sociological aspects with impacts on water resources a particular concern (Poore and Fries, 1985). Studies in the state of Karnataka found that annual water use of eucalypt and indigenous forest was equal to ~~the~~ annual rainfall in one plantation but, at another, water use by eucalypt plantations exceeded annual rainfall by 60% (Calder *et al*., 1992).

The deep roots of eucalypts adapt them to access groundwater at considerable depth. Under the Working for Water (WfW) programme in South Africa, alien invasive tree species, significantly including *Eucalyptus* species and hybrids, are a particular target for removal due to their implications for reducing water run-off from dryland catchments. Emerging concerns about the impacts of forestation, and in particular alien trees, on South Africa's water resources were raised in the 1990s (Le Maitre *et al*., 1996). E~~, e~~nsuing preliminary research formed~~ing~~ a key evidence base and motivation for the establishment of the government-funded WfW programme (van Wilgen *et al*., 1998). WfW has operated since 1995 as a resource protection and employment programme administered by the Department of Public Works with the support of multiple South African government departments (Department of Environmental Affairs, Undated). WfW recognises IAPs as a major threat compounding climate change, land use conversion and other pressures impacting water security and biodiversity, and imposing significant annual costs on the South African economy. To date, WfW has cleared more than one million hectares of IAPs (Department of Environmental Affairs, Undated).

Nevertheless, despite concerns expressed about the potential impacts of alien eucalyptus plantings on water resources in India (Sikka *et al*., 2003), little substantive science has thus far been conducted to assess their impact despite emerging concerns and the substantial standing biomass of eucalyptus trees. There is a need to quantify the impacts of IAPs on water security as an evidence base from which to judge the scale of impact particularly of eucalyptus trees on rural Indian dryland water and livelihood security, and to inform and prioritise control measures, as well as to protect biodiversity and wider dimensions of socio-ecological wellbeing.

The purpose of this study is to estimate water loss through evapotranspiration by alien eucalyptus trees in a range of dryland Indian villages in Rajasthan and Haryana states, and to compare this with livelihood water uses, both based on interviews with community leaders. Removal of trees would not be an acceptable strategy, robbing villages of shade and timber resources as well as exposing them to open ground and cropland evaporation. Consequently, literature-based studies of comparative evapotranspiration and ecosystem service provision respectively by alien eucalyptus trees and native neem (*Azadirachta indica*) provides a basis for assessing the water security implications and likely acceptability of a programme to replace eucalyptus with culturally valued native trees. These findings inform policy recommendations regarding the significance of 'thirsty' alien tree management as a contribution to water security in arid and semi-arid India. Findings are transferrable, with regional geographical and cultural adaptation, to other global arid and semi-arid regions facing similar challenges.

Methods

A mixed methods approach was undertaken to assess the extent of alien eucalypt presence, their likely water demand compared to village livelihoods, and the consequences of their potential replacement with native trees. Description and rationale for selection of the study sites is provided below. Three methods were then applied to address the problem: structured literature review; ecosystem services assessment of contrasting alien eucalyptus and native neem trees; and semi-structured interviews with informants from the selected villages.

Description and rationale for selection of the study sites

Two principal study areas were selected: northern Rajasthan state and southern Haryana state, collectively visiting eight villages. Selection of these study areas and specific villages was based on a number of factors. Firstly, both are semi-arid regions facing water security challenges. Secondly, improved water management measures had been promoted and undertaken in the targeted villages. These had been led in Rajasthan by the NGOs Tarun Bharat Sangh (TBS) and WaterHarvest, and in Haryana by Manav Rachna International Institute of Research and Studies or the Haryana state Forest Department. Thirdly, the range of villages selected was populated by varying numbers of eucalyptus trees. In all but one of these villages, the eucalypts were mature trees, long established as state Forest Departments had abandoned eucalypt planting for some years; the exception to this was Atarna village (Haryana) where privately-owned commercial hybrid eucalyptus plantations were planted on a five-year cycle. Summary data concerning these parameters are outlined in Table 1, with village locations illustrated in Figure 1.

Table 1: Relevant features of dryland villages surveyed in this study

[Table 1 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]

Village name	State	District	Annual District rainfall in mm [a]	Village population [b]	Number of households [c]	Number of eucalyptus trees [c]
Atarna	Haryana	Faridabad	697.6	1,791	400	10,000 (mainly plantation)
Panhera Khurd	Haryana	Faridabad		3,346	357	0
Beelwari	Rajasthan	Jaipur Gram (rural)	577.2	2,948	700	800
Dwarapur	Rajasthan	Alwar	630.9	1,823	365	300
Kishori	Rajasthan	Alwar		3,429	350	100
Malutana	Rajasthan	Alwar		2,325	550	1,000
Mandapur	Rajasthan	Alwar		657	50	2,000
Ramgarh Village	Rajasthan	Alwar		13,529	2,000	300

Sources:

[a] https://data.gov.in/catalog/district-rainfall-normal-mm-monthly-seasonal-and-annual-data-period-1951-2000 (accessed 09th September 2019)

[b] Census of India, 2011: http://censusindia.gov.in/ (accessed 09th September 2019)

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[c] Local informants (see Supplementary Material C)

Figure 1: Locations of villages surveyed in this study

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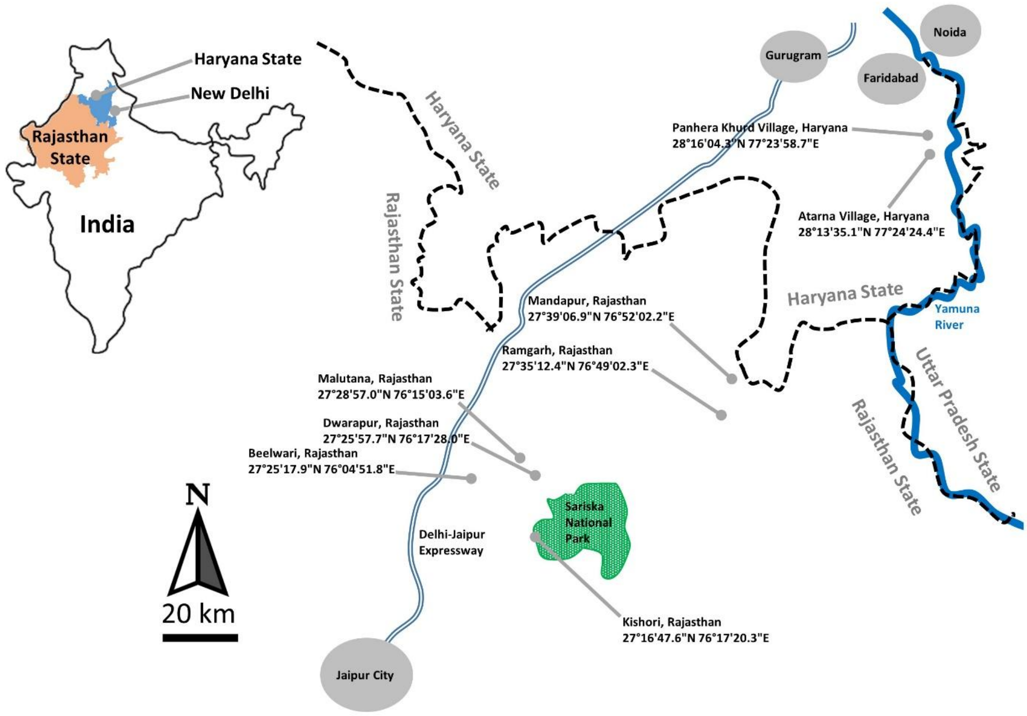

Structured literature reviews

Structured literature reviews were undertaken to assess evapotranspiration (ETP) rates respectively by species of *Eucalyptus*, alien to India, and a native, dryland-adapted species: the neem tree

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(*Azadirachta indica*) that occurs naturally and is planted widely in Rajasthan, Haryana and across South Asia. Structured reviews and their key findings are detailed in Supplementary Material A.

Ecosystem services assessment of alien and native tree species in the Indian dryland setting

Replacement of trees rather than simple tree removal would be important, as removal would promote open-ground evaporation and also rob villages of shade, storm buffering and other benefits. Consequently, there is a need to understand the relative benefits and disbenefits conferred on Indian dryland village communities by the different trees in order to inform a potential case for tree replacement.

Assessment of the ecosystem services accruing to village communities in dryland India respectively from eucalyptus and neem trees are documented in detail in Supplementary Material B. This ecosystem service assessment is based on the RAWES (Rapid Assessment of Wetland Ecosystem Services) approach (Ramsar Convention, 2018; RRC-EA, In press). Though RAWES specifically was developed for assessment of wetland ecosystem services recognizing practical time and resource limitations faced by operational staff, providing a simple, user-friendly, cost-effective approach supporting systemic assessment of the full range of wetland ecosystem services (McInnes and Everard, 2017), it is in essence adapted from a wider approach already used extensively across a range of habitat types (for example by Everard, 2009; Everard and Waters, 2013). RAWES is a rapid assessment approach integrating existing data with other forms of both quantitative and qualitative evidence to derive semi-quantitative assessments inclusive of all service types. The RAWES approach, rationale for selecting the underpinning ecosystem services classification framework, and practical deployment of RAWES are further described in Supplementary Material B. Supplementary Material B also describes and calculates ecosystem services indices (ESIs: indices of the quantum of ecosystem services generated) from these rapid ecosystem services assessments.

The potential contributions of ecosystem services respectively of native neem trees and alien eucalypts in a rural Indian dryland context were also structured using the RAWES approach, informed by literature-based evidence and supported in some cases by direct observations as well as the views of local informants in villages gathered during interviews reported in Supplementary Material C.

Semi-structured interviews with local informants

This third method entailed visiting the eight selected villages in the dryland Indian states of Haryana and Rajasthan where water stewardship and conservation measures were being practiced, but with differing numbers of eucalyptus. Responses to semi-structured interviews by selected authoritative figures closely connected with the villages (mainly Gram Panchayat members, in one case a teacher who had served in the village for over 20 years, and officers from the Forest Department Haryana including material from detailed village audits written up in Hindi) are summarised in Supplementary Material C. All respondents were informed of the purpose of this research, asked for their consent to use their anonymised responses, and offered the opportunity to withdraw at any time by contacting local people assisting with fieldwork.

Respondents generally provided values for village size, number of established eucalyptus trees and livelihood-related water uses in rounded numbers (area of village, area of arable area, etc.) This obviously suggests an approximation rather than a precise value. Reponses were also often provided in differing units, for example estimations of areas were variously expressed in acres, hectares or bighas. However, rather than seek more precise measurements, for which the research project was not resourced and local informants were unlikely to be able to provide, we worked with the information as provided acknowledging its inherent, largely unquantifiable uncertainties. The derived dataset is nonetheless informed by expert and locally embedded views, and so is relevant for the illustrative purposes of this analysis.

Results

Water use by alien eucalypt and native neem trees

Supplementary Material A documents structured literature reviews addressing evapotranspiration (ETP) rates respectively by eucalyptus and ~~a~~ native, dryland-adapted neem trees. The diverse literature enabled us to propose a daily ETP of 138 litres per mature eucalyptus averaged across the year. This ETP value is subject to uncertainty due to the paucity of literature upon which it based, and the differing units and approaches undertaken across a range of geographical areas in selected studies which would render quantification of uncertainty spurious. However, it is illustrative of the scale of water uptake and release into the atmosphere by eucalyptus trees in dryland settings. Little or no local recapture of this water is assumed for much of the year due to the semi-arid nature of surveyed regions.

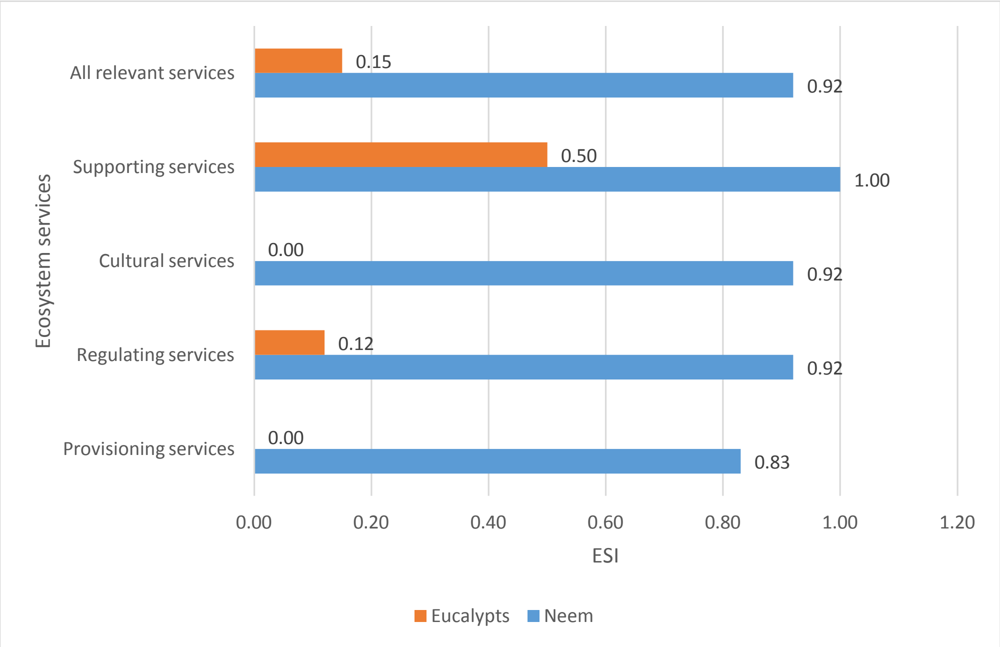
The even sparser literature on water release by neem trees led us to derive an estimate that annual average neem ETP is 50% that of eucalyptus (see Supplementary Material A). Though based on a small evidence base, for which estimation of uncertainty would therefore also only be likely to lead to a spurious sense precision, this estimate is nonetheless useful for the illustrative purpose of comparison of potential water savings were non-native eucalypts replaced with native neem trees.

Assessment of ecosystem services provided by alien eucalypt and native neem trees

Assessment of the ecosystem services accruing to village communities in dryland India respectively from eucalyptus and neem trees are summarised below as ESI values (as explained in Supplementary Material B), reflecting the degree to which maximum potential production of ecosystem services is attained. These different ESI values highlight the many more benefits provided by neem trees as compared to eucalypts in a dryland Indian context by ecosystem service category (see Figure 2).

Figure 2: ESI scores for production of ecosystem services respectively by neem and eucalyptus

[Figure 2 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



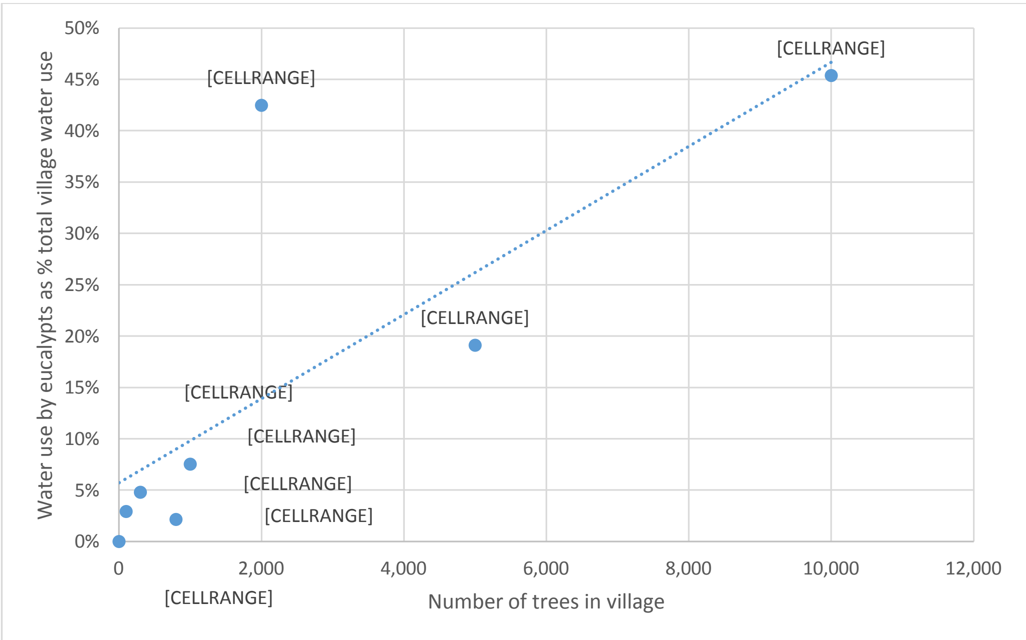
Relative water demand of eucalyptus trees compared with livelihood demands in sampled villages

Using the estimated ETP values for each tree species above, we calculated relative water demands respectively by eucalyptus trees and human livelihoods (domestic, livestock and irrigation) in the surveyed villages with varying numbers of eucalyptus trees. Figure 3 makes an initial observation of the water use by eucalypts as a percentage of the total village water use (livelihoods and ETP by eucalypts), plotted against number of trees in each village. An approximate trend line is plotted in Figure 3 based on 'face value' data, omitting any calculation of uncertainty. Aas explained when addressing the methods and results above, the uncertainties inherent in all data points and the trend line are therefore subject to an unquantified, and largely unquantifiable, degree of uncertainty. This evidence should therefore be regarded as illustrative of scale, rather than as definitive quantification.

With this caveat, it is unsurprising that larger numbers of 'thirsty' alien trees appear to consume a greater proportion of the total water demand in surveyed villages. However, comparison of values for total ETP by eucalypts and village-scale water use illustrates that demands from higher densities of eucalypts can be significant relative to livelihood water demands, potentially undermining other water efficiency measures undertaken in this dryland region.

Figure 3: Water use by eucalypts as % total village water use, plotted against number of trees in each village (with approximate trend line)

[Figure 3 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



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Comparative water demand were eucalypts replaced by native neem trees

Figure 4 illustrates water use by eucalypt trees as a percentage of total village water use (livelihoods and ETP by eucalypts), plotted against the volume of water if eucalypts are replaced with neem expressed as number of household livelihood demands (assuming that neem use 50% of the amount of water ~~than~~ compared to eucalypts). An apparent anomaly in trends in Figure 4 is the water use by the estimated 2,000 eucalypts in Mandapur village (Rajasthan), accounting for 42% of total village water use (livelihoods and ETP by eucalypts) yet replacement with neem would appear to account for a relatively small saving of 18 household livelihood demands. This anomaly is attributed to the small human population size of Mandapur village (50 households with 657 people), also reflecting the large distance of the point of Mandapur from the trend line in Figure 3. Figure 5 plots water use by eucalypt trees as a percentage of total of village water use (livelihoods and ETP by eucalypts), as well as the percentage savings in livelihood demands if all eucalypts were replaced with neem. (In Figure 5, water savings at Mandapur are consistent with the general trend across the series of villages.)

Figure 4: Water use by eucalypts as % total village water use, and amount of water saved if eucalypts are replaced with neem expressed as number of household livelihood demands

[Figure 4 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]

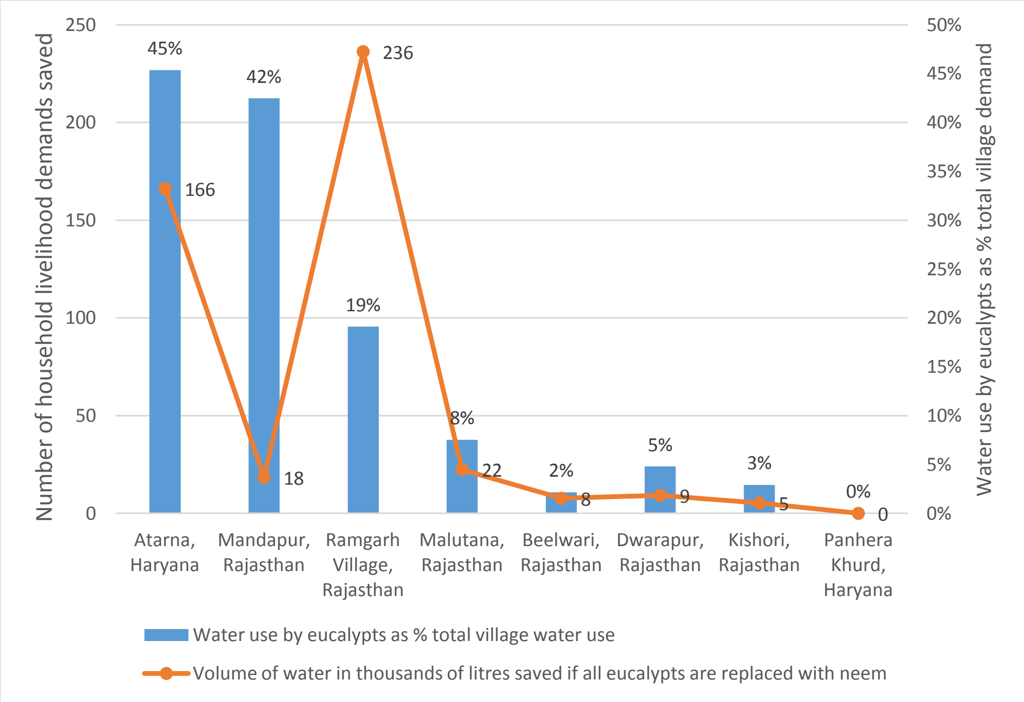
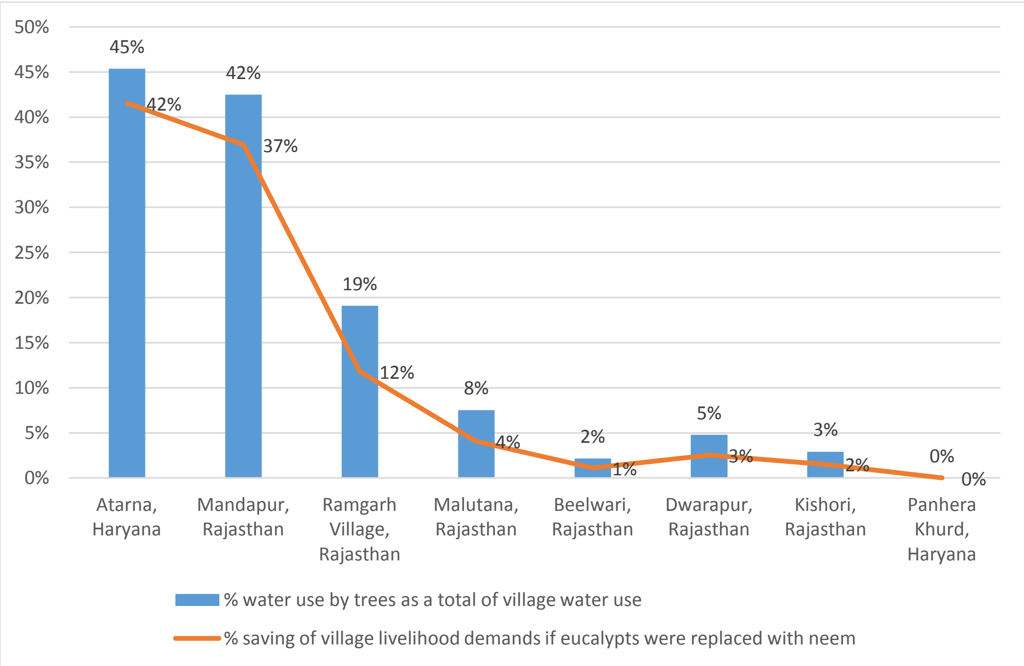


Figure 5: Water use by eucalypts as % total of village water use, and % saving of village livelihood demands if all eucalypts were replaced with neem

[Figure 5 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



Discussion

It is recognised that many input parameters provided by expert, local informants were rounded numbers. Consequently, water use, RAWES assessments and derived ESI scores are semi-quantitative, albeit based on transparently stated evidence some of which may be qualitative. Assessment methods using qualitative criteria to address data gaps or integrate differing forms of evidence are commonly critiqued. However, integration of qualitative with quantitative evaluations is essential for systemic sustainability assessment, as evaluations based only on criteria for which statistical data are available will be skewed towards only known concerns and priorities (McInnes and Everard, 2017). Omission of assessment of services for which evidence is otherwise lacking can lead to non-systemic conclusions and decision-making, potentially overlooking unforeseen problems and potential future risks. Semi-quantification is also routinely deployed in industry, regulation and other forms of decision-making, for example in assigning risk criteria when judging likelihood of timing, scale and reversibility of impacts.

Attempts to quantify uncertainties in this study would infer spurious accuracy, so findings are based on face value calculations alone which serve the principally illustrative purpose of this study.

Acknowledging this inherent uncertainty, findings across a range of different Indian dryland villages are nonetheless illustrative of the potential significance of eucalyptus trees for water security relative to livelihood demands, and hence the benefits of integrating alien tree management into water security policy and practice. Substantial savings in water would result in all but Panhera Khurd village (Haryana), which lacks eucalypts, were eucalyptus trees replaced with neem. These water savings achievable from tree replacement potentially account for the demands of up to 235 household livelihoods (Ramgarh village, Rajasthan) and 42% village livelihood demands (Atarna village, Haryana).

Furthermore, ecosystem services assessments illustrate how greater societal benefits across all ecosystem service categories are likely to accrue from replacement of eucalypts with native neem trees. Alien eucalypts do provide some supporting and regulating services (ESIs of 0.50 and 0.12 respectively), though no cultural and provisioning services were found by literature survey or discussion with village informants, and the overall societal values accruing from eucalypts was low (overall ESI for all services was 0.15). By contrast, substantial ecosystem service contributions were calculated from native neem trees (ESIs of 0.83, 0.92, 0.92, 1.00 and 0.92 respectively for provisioning, regulating, cultural, supporting and all service combined), including greater contributions to water security through much reduced theoretical evapotranspiration. The case for phased replacement of eucalypts with neem trees for water security, but also a range of linked ecosystem services, is therefore substantial. The substantially greater societal benefits and uses of neem trees suggests a high level of likely acceptance and engagement by village communities in tree replacement programmes.

Further research would add rigour and confidence to the quantitative case for alien tree management in central dryland India, where their implications for water security may potentially be problematic. Further substantiation of the range of linked ecosystem service benefits supporting rural livelihoods would also support the case for a tree replacement strategy. Additional insights could arise from analysis of the wider suite of parameters collected during the village surveys in this study, but which are not the primary focus of this paper. This additional information includes evidence of well depths, governance arrangements, areas of land under different cover (forest, housing, common land, housing and wasteland) and average household size. Further areas for expansion of this study include assessment of the broader suite of benefits likely to accrue from ~~that~~ improved water security resulting from alien tree management~~ might as a consequence of greater water security~~, such as improved food security, reduced drudgery in collecting water from remote sources and enhanced soil condition and biodiversity. ~~These~~ Further potential linked benefits ~~relate to~~ include addressing current risks ~~that may be~~ associated with the use of poor quality water ~~potentially~~ pumped from deeper, geologically contaminated groundwater strata, recognising that Rajasthan suffers extensively from geological deep groundwater contamination (Coyte *et al*., 2019), as well as expanding opportunities for improved rabi (dry season) crop productivity and possibly even production of a third jayad (late summer) crop. A further research gap is assessment of potential biodiversity benefits from tree replacement, unquantifiable in this study due to the extreme paucity of currently published information about the use of native neem trees by insects, birds and other taxa.

However, notwithstanding stated uncertainties and further research needs, this initial analysis presents sufficient indicative evidence that replacement of ‘thirsty’ alien with native trees is likely to be hydrologically and socially beneficial. Identification of propriety areas for alien tree management could be community-based, expert-driven, technological, or a combination of these approaches. Community-based approaches could entail providing local communities with simplified heuristics adapted from the village survey method presented in this paper. Forest Department officers with local expertise could also use their judgements as to where tree replacement measures would be likely to make the largest difference (noting that retaining eucalypts where waterlogging is a local problem may be beneficial). Technological means to broaden the geographical scale of assessment could include the use of remote sensing data to pick out the spectral signatures of eucalypt trees and stands, with a potential prioritisation being comparison with NDVI or other spectral signatures of wider land cover signifying water stress (for example Dzikiti *et al*., 2016). One immediate policy implication arises from Atarna, in Haryana state. Atarna was the only village surveyed with a privately-owned plantation of eucalypts, which was found indicatively to consume 45% of the total water used in the village. This raises issues of equity and wise use of water with respect to wider village water security. In this instance, an estimated 42% of the total current village livelihood water demand could be saved were the eucalypts replaced with an equivalent number of neem trees, making a significant contribution to water security in the village and locality.

The potential contribution of replacement of eucalyptus with native tree for water resource security may constitute an 'anchor service' (*sensu* Everard, 2014), or in other words a primary driver for decision-making around which further ecosystem service benefits can be planned. However, as indicated by ESIs calculated for neem as opposed to eucalyptus, replacement of 'thirsty' alien trees with native species would be highly likely to confer a wide range of linked ecosystem service benefits spanning medicinal, biodiversity, water resource and other benefits, consistent with an intentionally multi-beneficial 'systemic solutions' approach (Everard and McInnes, 2013).

These findings have generic relevance if adapted to the differing geographical and cultural contexts of other global arid and semi-arid settings facing linked threats of water shortage and alien tree invasion. The problem and its associated solutions are well-established in South Africa, evidenced by the Working for Water programme and its underpinning science base. However, as exemplified by the negative impacts of alien tree invasions on stream baseflow in north-central Portugal (Hawtree *et al*., 2015) and the depression of vulnerable groundwater resources in Pacific islands (Meyer *et al*., 2011), these linked issues may be more globally pervasive, potentially under-researched and inadequately integrated within policy responses.

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Conclusions

- Although resting on a number of stated assumptions, and subject to data inputs of varying confidence, the analyses in this paper provide illustrative evidence confirming the 'thirsty' nature of alien invasive eucalyptus trees as compared to native neem trees in a rural Indian dryland context.
- Illustrative evidence from the eight surveyed villages highlights that replacement of eucalypts with native neem trees may make a substantial potential contribution to water security, creating additional capacity for livelihood needs.
- Assessments within this study also recognise that many more ecosystem service benefits flow from native neem trees to local Indian dryland village communities compared with alien eucalypt trees.
- Whilst stands of eucalyptus may remain useful for addressing problems in waterlogged areas, replacement of eucalyptus trees with neem can make a potentially substantial as well as socially acceptable contribution to water security in dryland villages in India.
- These finding substantiate a growing case for cessation of eucalyptus plantings in water-stressed regions of India, and for replacement of these 'thirsty' trees with multi-beneficial native species.
- Biodiversity benefits could not be quantified due to the extreme paucity of currently published relevant information.
- Overall, there is a solid case for the integration of alien tree management into policy formulation to increase water security in the dryland states of India, as well as in other arid and semi-arid global areas sharing common challenges.

Acknowledgements

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Author contribution

This paper is the sole work of the author, with support for fieldwork acknowledged where appropriate.

Author information

Raw data sheets (hand-written and transcribed into Excel files) are held confidentially by the author but can be made available to other researchers, with summary data and a sample field survey sheet uploaded as Supplementary Material C. The Author has no competing interests, and is also the corresponding author.

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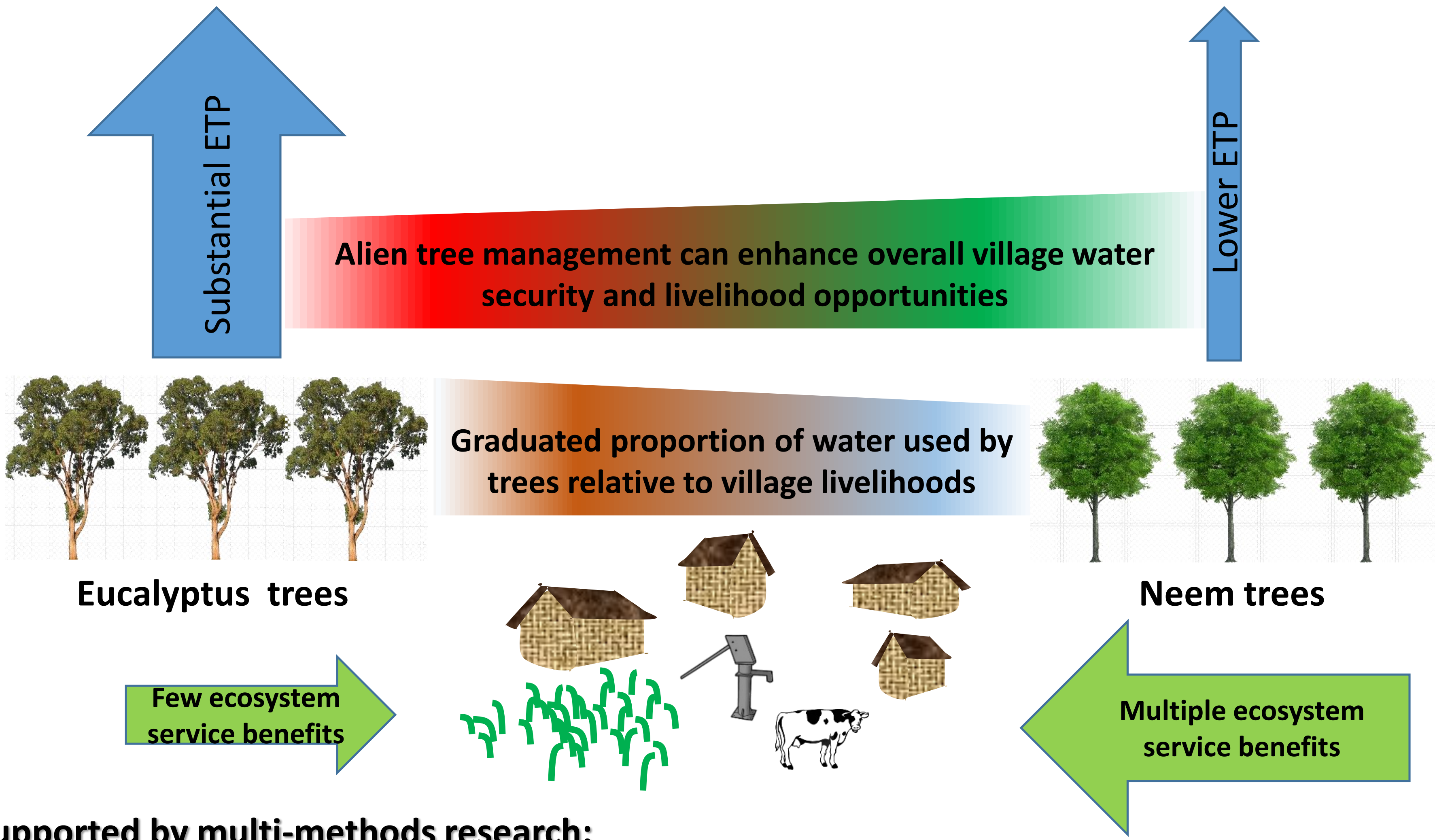
Supplementary information

Three Supplementary Material files are uploaded with this contribution, as indicated in the text of the main paper:

- Supplementary Material A: Literature review concerning water used by eucalypts and neem trees in Indian drylands;
- Supplementary Material B: Literature review concerning ecosystem services provided by eucalypts and neem trees in Indian drylands; and
- Supplementary Material C: Spreadsheet containing summary data on water surveyed villages, including a sample field survey sheet.

*Graphical Abstract



Supported by multi-methods research:

1. **Structured literature review**
2. **Counting of trees and assessment of livelihood water demands in a range of villages**
3. **Ecosystem service assessment of (alien) eucalypts and (native) neem trees in India**

*Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Can management of 'thirsty' alien trees improve water security in semi-arid India?

Dr Mark Everard, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK (E: mark.everard@uwe.ac.uk; M: +44-(0)-7747-120019).

Research highlights

- Alien invasive eucalyptus trees consume more water than native neem trees in India
- Replacing eucalypts with neem may make a substantial contribution to water security
- Multiple ecosystem service benefits may also stem from replacement neem trees
- There is a case for integrating alien tree management into water security policy
- Biodiversity benefits were unquantifiable due to paucity of published information

Can management of 'thirsty' alien trees improve water security in semi-arid India?

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Abstract

Arid and semi-arid regions of central India receive scarce and episodic precipitation during the short monsoon season, and also experience substantial evaporation. Traditional and innovative water harvesting and governance practices improve water stewardship, or abate some impacts of intensive mechanised water extraction. However, significant numbers of alien trees, in particular *Eucalyptus* species with high water demands, populate some regions practicing progressive water stewardship. The water demands of these trees can potentially undermine efforts to achieve water security. Through interviews with community leaders in Indian villages with differing eucalyptus tree densities, water loss through evapotranspiration compared with livelihood demands was approximated. Literature review of the water demands and ecosystem services provided respectively by alien eucalypts and native, culturally valued neem trees supports assessment of the likely benefits and acceptability of a replacement programme favouring native trees. Although data limitations mean that the findings of this study are necessarily uncertain, they nonetheless illustrate the likely scale of impact, substantiating the case for alien tree management as an important contribution to water security. Alien vegetation management practices as a contribution to water security are already firmly established in South Africa, and are likely to yield equivalent benefits if translated to dryland India.

Key words

Dryland; alien invasive plants; evapotranspiration; water management; ecosystem services; neem

Introduction

India spans a diversity of climates and microclimates, from arid desert to the north-west to glaciers and alpine tundra in the Himalayan uplands and humid tropics in the south-west coast and island territories. The drier lands range from the fully arid Thar Desert, spanning approximately half of the state of Rajasthan and much of Gujarat, towards semi-arid regions receiving scarce rainfall extending westwards across the rest of Rajasthan and into northern Madhya Pradesh, Haryana and regions of adjacent states. The pronounced seasonality of rainfall predominantly during a short monsoon season, associated with high evaporation rates throughout the year, result in substantial dependence on groundwater for domestic, agricultural and other uses. Water scarcity is a pressing issue for both rural and urban livelihoods. Analysis of satellite gravity data indicates that current groundwater abstraction from the transboundary Indo-Gangetic Basin, comprising 25% of global groundwater withdrawals used to sustain agriculture in Pakistan, India, Nepal and Bangladesh, is unsustainable but also compromised by extensive contamination (MacDonald *et al*., 2016).

A diversity of innovations for harvesting and storage of seasonal run-off, promoting aquifer recharge, are found across the region representing centuries of geographically and culturally adapted traditional knowledge adapting to local geographic and socio-economic conditions as well as historic changes in climate (Pandey *et al*., 2003; Gunnell and Krishnamurthy, 2003). However, intensive, mechanised water management solutions, such as tube wells and dam-and-transfer schemes, have led to a decline in traditional, community-based stewardship and, consequently, declining water security, compounded by centralised government control, economic pressures and climate change (Everard, 2015). Running counter to this trend has been a diversity of regional initiatives to reinstate locally adapted water harvesting and stewardship, especially in southern and western India (Bhanja *et al*., 2017). These initiatives, together with promotion of water efficiency measures, has seen some aquifer recovery (Van Meter *et al*., 2016; Bhanja *et al*., 2017).

Similar challenges, allied with renewed interest in groundwater recharge as part of a solution, are observed in other dryland regions globally. In Europe, seasonal deficits at village level in Portugal are observed as holiday-related rises in population coincide with the dry season, potentially compounded in future by climate change, leading to proposals for conjunctive water management based on surface water stored in small dams and groundwater (Soares *et al*., 2019). Terêncio *et al*. (2017) use a Multi Criteria Analysis (MCA) approach based on a Geographic Information System (GIS) to improve identification of optimal implementation of rainwater harvesting systems in this situation. Illustrative of wider groundwater recharge practices in Middle Eastern and North African countries, Salameh *et al*. (2019) review case studies in Jordan to assess conditions for the successful implementation of managed aquifer recharge. In west Africa, the Burkinabé Government now recognises and is seeking to promote the value and integration of nature-based solutions (NBS) and engineered infrastructure for water management in the Central Plateau of Burkina Faso (Government of Burkina Faso, 2018). In South America, promotion of local nature-based solutions for water storage and infiltration are being promoted by Peru's national government in the Ayacucho region to improve rural livelihood expectations, increase recharge capacities for reservoirs serving urban needs and address susceptibility to climate change in this semi-arid upland ecosystem (Ministerio de Agricultura y Riego, n.d.).In dryland India, some regions in which progress is being made with water stewardship nevertheless contain significant numbers of alien tree species with high water demands. Particular concern has been expressed about the potential for alien *Eucalyptus* plantations to undermine community efforts to achieve water security (Srinivasan *et al*., 2015). Of India's estimated 45,000 plant species (Ali, 1999), roughly 40% are alien and, of this, approximately 25% are considered invasive alien plants (IAPs) (Raghubanshi *et al*., 2005). Significant amongst these alien trees are eucalypts (various large tree species of the genus *Eucalyptus* particularly including their hybrids). Eucalypts, native to Australia, were first planted in India on the Nandi Hills near Bangalore around 1790 by Tippu Sultan, ruler of Mysore (Shyam Sundar, 1984). By 1988, over 1,000,000 ha of eucalypt plantations had been established across India, by majority resulting from activities of State Forest Departments and Forest Development Corporations, with a further 6,000 million seedlings planted in private lands (Sandhu *et al*., 1988). The intent behind promotion of widespread eucalypt plantations was to convert natural forests of low perceived value to improve timber productivity and generate government revenue, with economic considerations narrowly focused on yield of timber including pulpwood (Mathur *et al*., 1984). Further reasons for the planting of eucalyptus, particularly hybrids, was as a means to counter the serious problem of waterlogging and secondary soil salinization in canal-irrigated arid and semi-arid regions (Ram *et al*., 2011).

The alien status of eucalyptus in India was one of many factors resulting a study by the FAO (UN Food and Agriculture Organization) on the benefits of plantations, taking into account wider ecological, economic, hydrological and sociological aspects with impacts on water resources a particular concern (Poore and Fries, 1985). Studies in the state of Karnataka found that annual water use of eucalypt and indigenous forest was equal to annual rainfall in one plantation but, at another, water use by eucalypt plantations exceeded annual rainfall by 60% (Calder *et al*., 1992).

The deep roots of eucalypts adapt them to access groundwater at considerable depth. Under the Working for Water (WfW) programme in South Africa, alien invasive tree species, significantly including *Eucalyptus* species and hybrids, are a particular target for removal due to their implications for reducing water run-off from dryland catchments. Emerging concerns about the impacts of forestation, and in particular alien trees, on South Africa's water resources were raised in the 1990s (Le Maitre *et al*., 1996). Ensuing preliminary research formed a key evidence base and motivation for the establishment of the government-funded WfW programme (van Wilgen *et al*., 1998). WfW has operated since 1995 as a resource protection and employment programme administered by the

Department of Public Works with the support of multiple South African government departments (Department of Environmental Affairs, Undated). WfW recognises IAPs as a major threat compounding climate change, land use conversion and other pressures impacting water security and biodiversity, and imposing significant annual costs on the South African economy. To date, WfW has cleared more than one million hectares of IAPs (Department of Environmental Affairs, Undated).

Nevertheless, despite concerns expressed about the potential impacts of alien eucalyptus plantings on water resources in India (Sikka *et al*., 2003), little substantive science has thus far been conducted to assess their impact despite emerging concerns and the substantial standing biomass of eucalyptus trees. There is a need to quantify the impacts of IAPs on water security as an evidence base from which to judge the scale of impact particularly of eucalyptus trees on rural Indian dryland water and livelihood security, and to inform and prioritise control measures, as well as to protect biodiversity and wider dimensions of socio-ecological wellbeing.

The purpose of this study is to estimate water loss through evapotranspiration by alien eucalyptus trees in a range of dryland Indian villages in Rajasthan and Haryana states, and to compare this with livelihood water uses, both based on interviews with community leaders. Removal of trees would not be an acceptable strategy, robbing villages of shade and timber resources as well as exposing them to open ground and cropland evaporation. Consequently, literature-based studies of comparative evapotranspiration and ecosystem service provision respectively by alien eucalyptus trees and native neem (*Azadirachta indica*) provides a basis for assessing the water security implications and likely acceptability of a programme to replace eucalyptus with culturally valued native trees. These findings inform policy recommendations regarding the significance of 'thirsty' alien tree management as a contribution to water security in arid and semi-arid India. Findings are transferrable, with regional geographical and cultural adaptation, to other global arid and semi-arid regions facing similar challenges.

Methods

A mixed methods approach was undertaken to assess the extent of alien eucalypt presence, their likely water demand compared to village livelihoods, and the consequences of their potential replacement with native trees. Description and rationale for selection of the study sites is provided below. Three methods were then applied to address the problem: structured literature review; ecosystem services assessment of contrasting alien eucalyptus and native neem trees; and semi-structured interviews with informants from the selected villages.

Description and rationale for selection of the study sites

Two principal study areas were selected: northern Rajasthan state and southern Haryana state, collectively visiting eight villages. Selection of these study areas and specific villages was based on a number of factors. Firstly, both are semi-arid regions facing water security challenges. Secondly, improved water management measures had been promoted and undertaken in the targeted villages. These had been led in Rajasthan by the NGOs Tarun Bharat Sangh (TBS) and WaterHarvest, and in Haryana by Manav Rachna International Institute of Research and Studies or the Haryana state Forest Department. Thirdly, the range of villages selected was populated by varying numbers of eucalyptus trees. In all but one of these villages, the eucalypts were mature trees, long established as state Forest Departments had abandoned eucalypt planting for some years; the exception to this was Atarna village (Haryana) where privately-owned commercial hybrid eucalyptus plantations were planted on a five-year cycle. Summary data concerning these parameters are outlined in Table 1, with village locations illustrated in Figure 1.

Table 1: Relevant features of dryland villages surveyed in this study

[Table 1 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]

Village name	State	District	Annual District rainfall in mm [a]	Village population [b]	Number of households [c]	Number of eucalyptus trees [c]
Atarna	Haryana	Faridabad	697.6	1,791	400	10,000 (mainly plantation)
Panhera Khurd	Haryana	Faridabad		3,346	357	0
Beelwari	Rajasthan	Jaipur Gram (rural)	577.2	2,948	700	800
Dwarapur	Rajasthan	Alwar		1,823	365	300
Kishori	Rajasthan	Alwar		3,429	350	100
Malutana	Rajasthan	Alwar	630.9	2,325	550	1,000
Mandapur	Rajasthan	Alwar		657	50	2,000
Ramgarh Village	Rajasthan	Alwar		13,529	2,000	300

Sources:

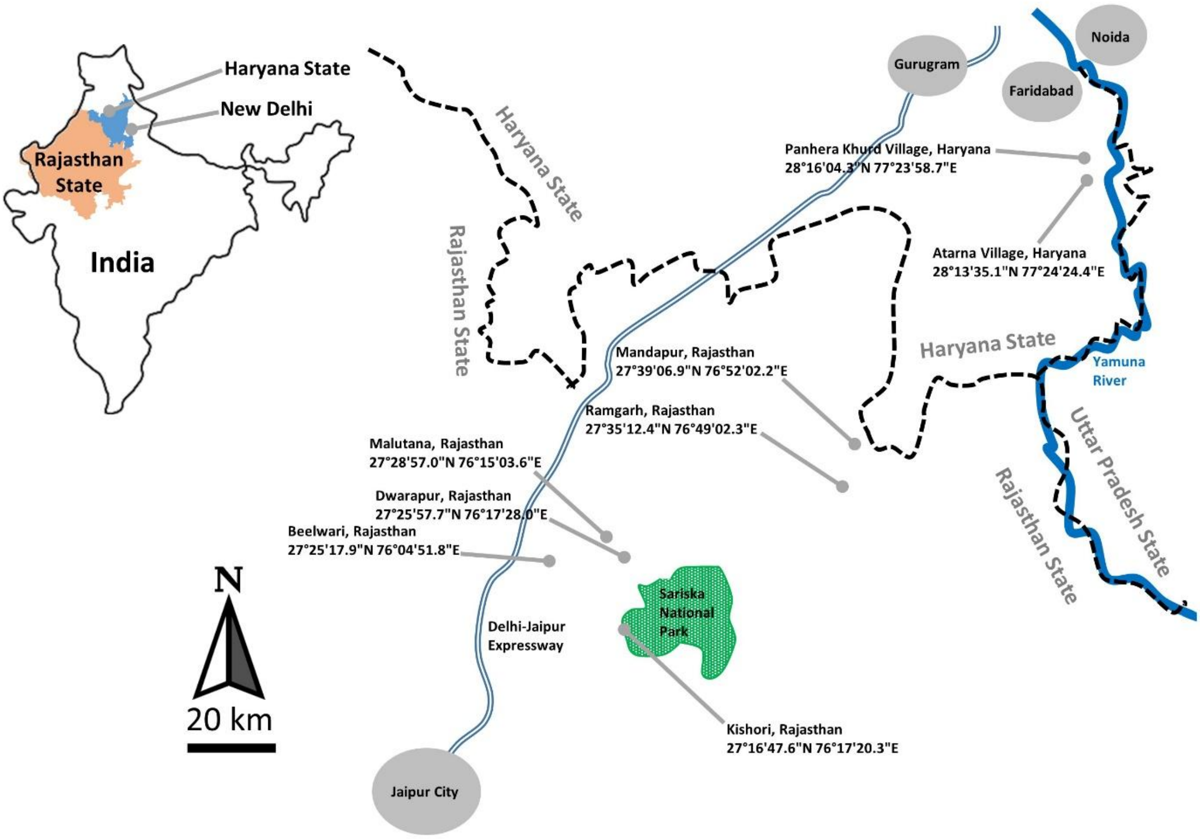
[a] https://data.gov.in/catalog/district-rainfall-normal-mm-monthly-seasonal-and-annual-data-period-1951-2000 (accessed 09th September 2019)

[b] Census of India, 2011: http://censusindia.gov.in/ (accessed 09th September 2019)

[c] Local informants (see Supplementary Material C)

Figure 1: Locations of villages surveyed in this study

[Figure 1 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



Structured literature reviews

Structured literature reviews were undertaken to assess evapotranspiration (ETP) rates respectively by species of *Eucalyptus*, alien to India, and a native, dryland-adapted species: the neem tree (*Azadirachta indica*) that occurs naturally and is planted widely in Rajasthan, Haryana and across South Asia. Structured reviews and their key findings are detailed in Supplementary Material A.

Ecosystem services assessment of alien and native tree species in the Indian dryland setting

Replacement of trees rather than simple tree removal would be important, as removal would promote open-ground evaporation and also rob villages of shade, storm buffering and other benefits. Consequently, there is a need to understand the relative benefits and disbenefits conferred on Indian dryland village communities by the different trees in order to inform a potential case for tree replacement.

Assessment of the ecosystem services accruing to village communities in dryland India respectively from eucalyptus and neem trees are documented in detail in Supplementary Material B. This ecosystem service assessment is based on the RAWES (Rapid Assessment of Wetland Ecosystem Services) approach (Ramsar Convention, 2018; RRC-EA, In press). Though RAWES specifically was developed for assessment of wetland ecosystem services recognizing practical time and resource limitations faced by operational staff, providing a simple, user-friendly, cost-effective approach supporting systemic assessment of the full range of wetland ecosystem services (McInnes and Everard, 2017), it is in essence adapted from a wider approach already used extensively across a range of habitat types (for example by Everard, 2009; Everard and Waters, 2013). RAWES is a rapid assessment approach integrating existing data with other forms of both quantitative and qualitative evidence to derive semi-quantitative assessments inclusive of all service types. The RAWES approach, rationale for selecting the underpinning ecosystem services classification framework, and practical deployment of RAWES are further described in Supplementary Material B. Supplementary Material B also describes and calculates ecosystem services indices (ESIs: indices of the quantum of ecosystem services generated) from these rapid ecosystem services assessments.

The potential contributions of ecosystem services respectively of native neem trees and alien eucalypts in a rural Indian dryland context were also structured using the RAWES approach, informed by literature-based evidence and supported in some cases by direct observations as well as the views of local informants in villages gathered during interviews reported in Supplementary Material C.

Semi-structured interviews with local informants

This third method entailed visiting the eight selected villages in the dryland Indian states of Haryana and Rajasthan where water stewardship and conservation measures were being practiced, but with differing numbers of eucalyptus. Responses to semi-structured interviews by selected authoritative figures closely connected with the villages (mainly Gram Panchayat members, in one case a teacher who had served in the village for over 20 years, and officers from the Forest Department Haryana including material from detailed village audits written up in Hindi) are summarised in Supplementary Material C. All respondents were informed of the purpose of this research, asked for their consent to use their anonymised responses, and offered the opportunity to withdraw at any time by contacting local people assisting with fieldwork.

Respondents generally provided values for village size, number of established eucalyptus trees and livelihood-related water uses in rounded numbers (area of village, area of arable area, etc.) This obviously suggests an approximation rather than a precise value. Reponses were also often provided in differing units, for example estimations of areas were variously expressed in acres, hectares or bighas. However, rather than seek more precise measurements, for which the research project was not resourced and local informants were unlikely to be able to provide, we worked with the information as provided acknowledging its inherent, largely unquantifiable uncertainties. The derived dataset is nonetheless informed by expert and locally embedded views, and so is relevant for the illustrative purposes of this analysis.

Results

Water use by alien eucalypt and native neem trees

Supplementary Material A documents structured literature reviews addressing evapotranspiration (ETP) rates respectively by eucalyptus and native, dryland-adapted neem trees. The diverse literature enabled us to propose a daily ETP of 138 litres per mature eucalyptus averaged across the year. This ETP value is subject to uncertainty due to the paucity of literature upon which it based, and the differing units and approaches undertaken across a range of geographical areas in selected studies which would render quantification of uncertainty spurious. However, it is illustrative of the scale of water uptake and release into the atmosphere by eucalyptus trees in dryland settings. Little or no local recapture of this water is assumed for much of the year due to the semi-arid nature of surveyed regions.

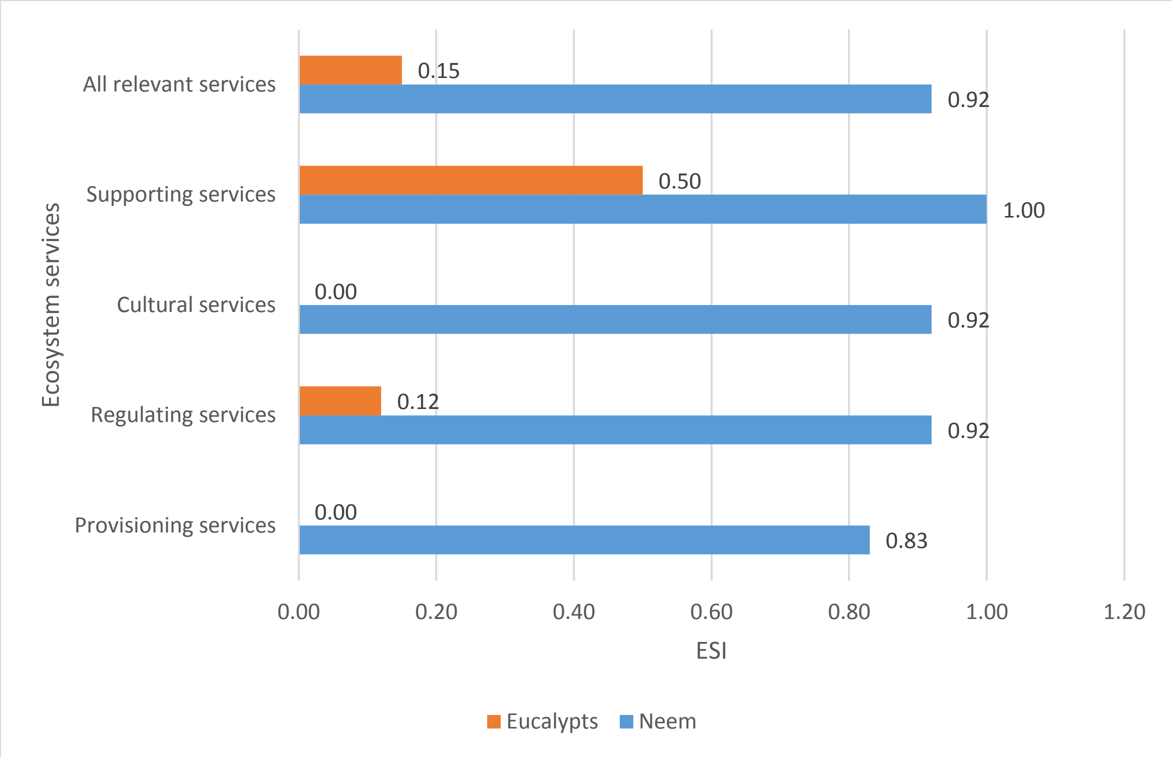
The even sparser literature on water release by neem trees led us to derive an estimate that annual average neem ETP is 50% that of eucalyptus (see Supplementary Material A). Though based on a small evidence base, for which estimation of uncertainty would therefore also only be likely to lead to a spurious sense precision, this estimate is nonetheless useful for the illustrative purpose of comparison of potential water savings were non-native eucalypts replaced with native neem trees.

Assessment of ecosystem services provided by alien eucalypt and native neem trees

Assessment of the ecosystem services accruing to village communities in dryland India respectively from eucalyptus and neem trees are summarised below as ESI values (as explained in Supplementary Material B), reflecting the degree to which maximum potential production of ecosystem services is attained. These different ESI values highlight the many more benefits provided by neem trees as compared to eucalypts in a dryland Indian context by ecosystem service category (see Figure 2).

Figure 2: ESI scores for production of ecosystem services respectively by neem and eucalyptus

[Figure 2 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



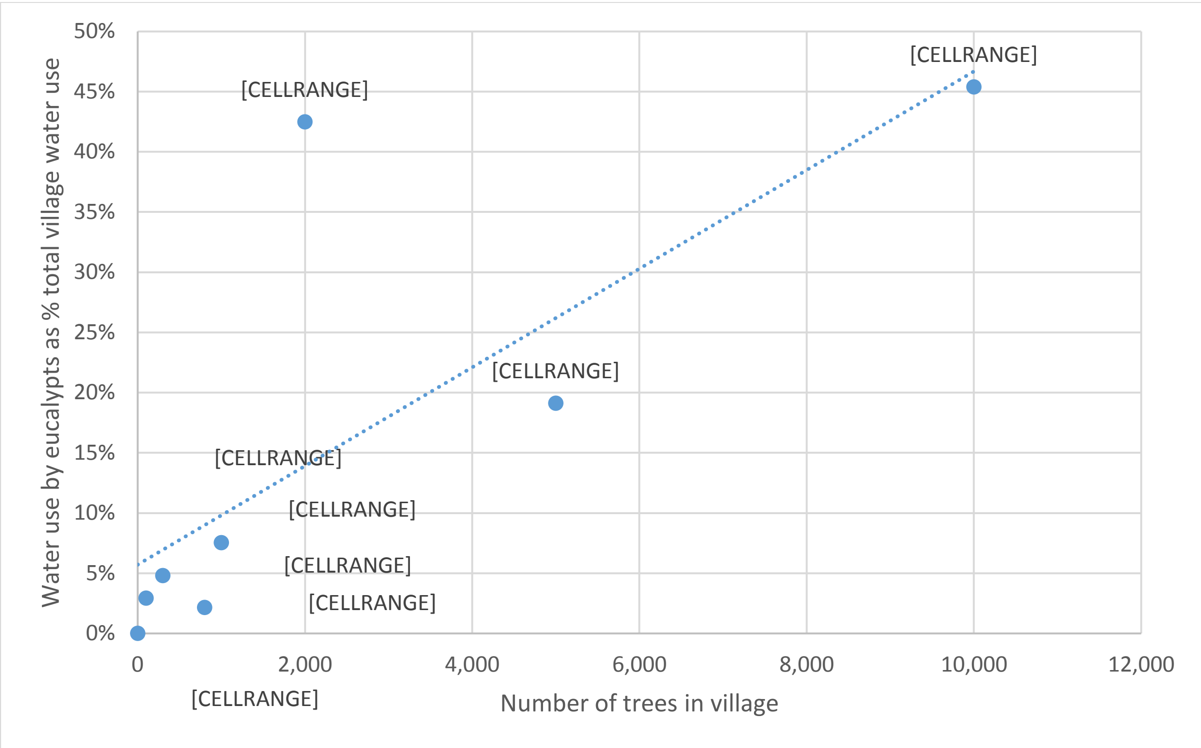
Relative water demand of eucalyptus trees compared with livelihood demands in sampled villages

Using the estimated ETP values for each tree species above, we calculated relative water demands respectively by eucalyptus trees and human livelihoods (domestic, livestock and irrigation) in the surveyed villages with varying numbers of eucalyptus trees. Figure 3 makes an initial observation of the water use by eucalypts as a percentage of the total village water use (livelihoods and ETP by eucalypts), plotted against number of trees in each village. An approximate trend line is plotted in Figure 3 based on 'face value' data, omitting any calculation of uncertainty. As explained when addressing the methods and results above, the uncertainties inherent in all data points and the trend line are therefore subject to an unquantified, and largely unquantifiable, degree of uncertainty. This evidence should therefore be regarded as illustrative of scale, rather than as definitive quantification.

With this caveat, it is unsurprising that larger numbers of 'thirsty' alien trees appear to consume a greater proportion of the total water demand in surveyed villages. However, comparison of values for total ETP by eucalypts and village-scale water use illustrates that demands from higher densities of eucalypts can be significant relative to livelihood water demands, potentially undermining other water efficiency measures undertaken in this dryland region.

Figure 3: Water use by eucalypts as % total village water use, plotted against number of trees in each village (with approximate trend line)

[Figure 3 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



Comparative water demand were eucalypts replaced by native neem trees

Figure 4 illustrates water use by eucalypt trees as a percentage of total village water use (livelihoods and ETP by eucalypts), plotted against the volume of water if eucalypts are replaced with neem expressed as number of household livelihood demands (assuming that neem use 50% of the amount of water compared to eucalypts). An apparent anomaly in trends in Figure 4 is the water use by the estimated 2,000 eucalypts in Mandapur village (Rajasthan), accounting for 42% of total village water use (livelihoods and ETP by eucalypts) yet replacement with neem would appear to account for a relatively small saving of 18 household livelihood demands. This anomaly is attributed to the small human population size of Mandapur village (50 households with 657 people), also reflecting the large distance of the point of Mandapur from the trend line in Figure 3. Figure 5 plots water use by eucalypt trees as a percentage of total of village water use (livelihoods and ETP by eucalypts), as well as the percentage savings in livelihood demands if all eucalypts were replaced with neem. (In Figure 5, water savings at Mandapur are consistent with the general trend across the series of villages.)

Figure 4: Water use by eucalypts as % total village water use, and amount of water saved if eucalypts are replaced with neem expressed as number of household livelihood demands

[Figure 4 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]

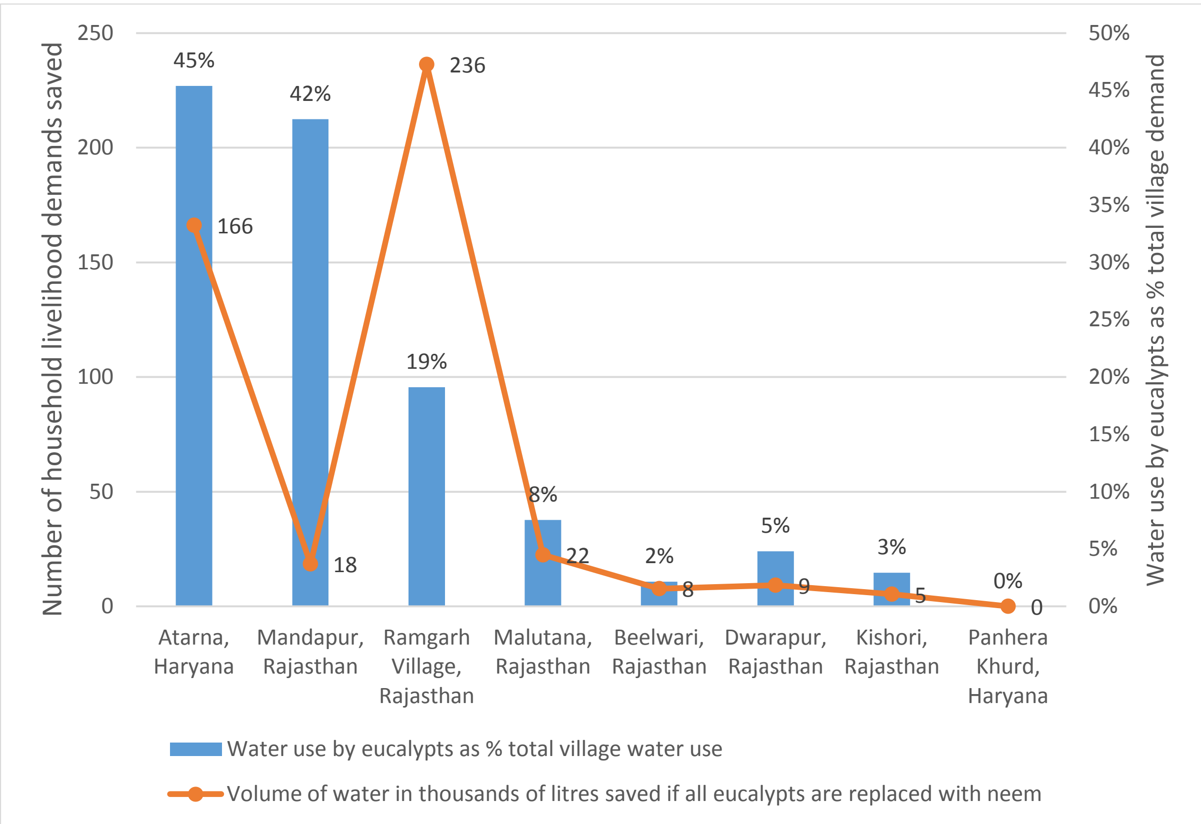
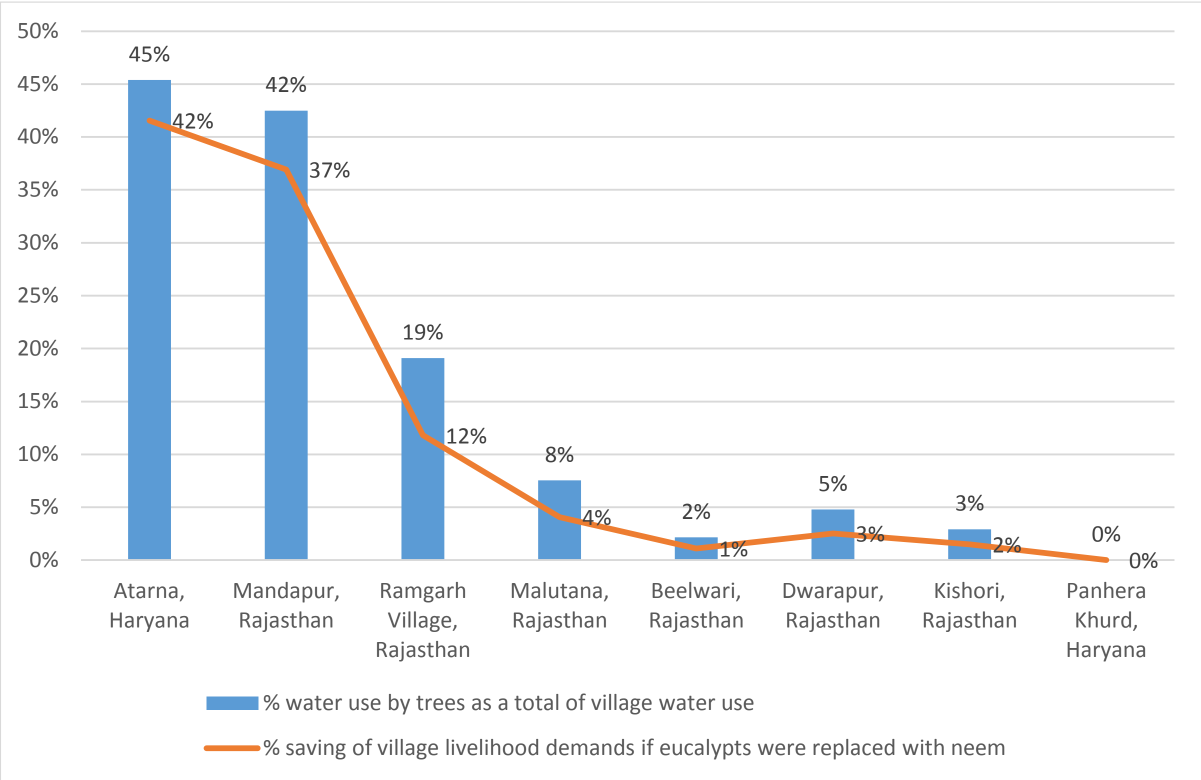


Figure 5: Water use by eucalypts as % total of village water use, and % saving of village livelihood demands if all eucalypts were replaced with neem

[Figure 5 is uploaded separately as requested by journal guidelines, but reproduced here to aid reviewers]



Discussion

It is recognised that many input parameters provided by expert, local informants were rounded numbers. Consequently, water use, RAWES assessments and derived ESI scores are semi-quantitative, albeit based on transparently stated evidence some of which may be qualitative. Assessment methods using qualitative criteria to address data gaps or integrate differing forms of evidence are commonly critiqued. However, integration of qualitative with quantitative evaluations is essential for systemic sustainability assessment, as evaluations based only on criteria for which statistical data are available will be skewed towards only known concerns and priorities (McInnes and Everard, 2017). Omission of assessment of services for which evidence is otherwise lacking can lead to non-systemic conclusions and decision-making, potentially overlooking unforeseen problems and potential future risks. Semi-quantification is also routinely deployed in industry, regulation and other forms of decision-making, for example in assigning risk criteria when judging likelihood of timing, scale and reversibility of impacts. Attempts to quantify uncertainties in this study would infer spurious accuracy, so findings are based on face value calculations alone which serve the principally illustrative purpose of this study.

Acknowledging this inherent uncertainty, findings across a range of different Indian dryland villages are nonetheless illustrative of the potential significance of eucalyptus trees for water security relative to livelihood demands, and hence the benefits of integrating alien tree management into water security policy and practice. Substantial savings in water would result in all but Panhera Khurd village (Haryana), which lacks eucalypts, were eucalyptus trees replaced with neem. These water savings achievable from tree replacement potentially account for the demands of up to 235 household livelihoods (Ramgarh village, Rajasthan) and 42% village livelihood demands (Atarna village, Haryana).

Furthermore, ecosystem services assessments illustrate how greater societal benefits across all ecosystem service categories are likely to accrue from replacement of eucalypts with native neem trees. Alien eucalypts do provide some supporting and regulating services (ESIs of 0.50 and 0.12 respectively), though no cultural and provisioning services were found by literature survey or discussion with village informants, and the overall societal values accruing from eucalypts was low (overall ESI for all services was 0.15). By contrast, substantial ecosystem service contributions were calculated from native neem trees (ESIs of 0.83, 0.92, 0.92, 1.00 and 0.92 respectively for provisioning, regulating, cultural, supporting and all service combined), including greater contributions to water security through much reduced theoretical evapotranspiration. The case for phased replacement of eucalypts with neem trees for water security, but also a range of linked ecosystem services, is therefore substantial. The substantially greater societal benefits and uses of neem trees suggests a high level of likely acceptance and engagement by village communities in tree replacement programmes.

Further research would add rigour and confidence to the quantitative case for alien tree management in central dryland India, where their implications for water security may potentially be problematic. Further substantiation of the range of linked ecosystem service benefits supporting rural livelihoods would also support the case for a tree replacement strategy. Additional insights could arise from analysis of the wider suite of parameters collected during the village surveys in this study, but which are not the primary focus of this paper. This additional information includes evidence of well depths, governance arrangements, areas of land under different cover (forest, housing, common land, housing and wasteland) and average household size. Further areas for expansion of this study include assessment of the broader suite of benefits likely to accrue from improved water security resulting from alien tree management, such as improved food security, reduced drudgery in collecting water from remote sources and enhanced soil condition and biodiversity. Further potential linked benefits include addressing current risks associated with the use of poor quality water pumped from deeper, geologically contaminated groundwater strata, recognising that Rajasthan suffers extensively from geological deep groundwater contamination (Coyte *et al*., 2019), as well as expanding opportunities for improved rabi (dry season) crop productivity and possibly even production of a third jayad (late summer) crop. A further research gap is assessment of potential biodiversity benefits from tree replacement, unquantifiable in this study due to the extreme paucity of currently published information about the use of native neem trees by insects, birds and other taxa.

However, notwithstanding stated uncertainties and further research needs, this initial analysis presents sufficient indicative evidence that replacement of ‘thirsty’ alien with native trees is likely to be hydrologically and socially beneficial. Identification of propriety areas for alien tree management could be community-based, expert-driven, technological, or a combination of these approaches. Community-based approaches could entail providing local communities with simplified heuristics adapted from the village survey method presented in this paper. Forest Department officers with local expertise could also use their judgements as to where tree replacement measures would be likely to make the largest difference (noting that retaining eucalypts where waterlogging is a local problem may be beneficial). Technological means to broaden the geographical scale of assessment could include the use of remote sensing data to pick out the spectral signatures of eucalypt trees and stands, with a potential prioritisation being comparison with NDVI or other spectral signatures of wider land cover signifying water stress (for example Dzikiti *et al*., 2016). One immediate policy implication arises from Atarna, in Haryana state. Atarna was the only village surveyed with a privately-owned plantation of eucalypts, which was found indicatively to consume 45% of the total water used in the village. This raises issues of equity and wise use of water with respect to wider village water security. In this instance, an estimated 42% of the total current village livelihood water demand could be saved were the eucalypts replaced with an equivalent number of neem trees, making a significant contribution to water security in the village and locality.

The potential contribution of replacement of eucalyptus with native tree for water resource security may constitute an 'anchor service' (*sensu* Everard, 2014), or in other words a primary driver for decision-making around which further ecosystem service benefits can be planned. However, as indicated by ESIs calculated for neem as opposed to eucalyptus, replacement of 'thirsty' alien trees with native species would be highly likely to confer a wide range of linked ecosystem service benefits spanning medicinal, biodiversity, water resource and other benefits, consistent with an intentionally multi-beneficial 'systemic solutions' approach (Everard and McInnes, 2013).

These findings have generic relevance if adapted to the differing geographical and cultural contexts of other global arid and semi-arid settings facing linked threats of water shortage and alien tree invasion. The problem and its associated solutions are well-established in South Africa, evidenced by the Working for Water programme and its underpinning science base. However, as exemplified by the negative impacts of alien tree invasions on stream baseflow in north-central Portugal (Hawtree *et al*., 2015) and the depression of vulnerable groundwater resources in Pacific islands (Meyer *et al*., 2011), these linked issues may be more globally pervasive, potentially under-researched and inadequately integrated within policy responses.

Conclusions

- Although resting on a number of stated assumptions, and subject to data inputs of varying confidence, the analyses in this paper provide illustrative evidence confirming the 'thirsty' nature of alien invasive eucalyptus trees as compared to native neem trees in a rural Indian dryland context.
- Illustrative evidence from the eight surveyed villages highlights that replacement of eucalypts with native neem trees may make a substantial potential contribution to water security, creating additional capacity for livelihood needs.
- Assessments within this study also recognise that many more ecosystem service benefits flow from native neem trees to local Indian dryland village communities compared with alien eucalypt trees.
- Whilst stands of eucalyptus may remain useful for addressing problems in waterlogged areas, replacement of eucalyptus trees with neem can make a potentially substantial as well as socially acceptable contribution to water security in dryland villages in India.
- These finding substantiate a growing case for cessation of eucalyptus plantings in water-stressed regions of India, and for replacement of these 'thirsty' trees with multi-beneficial native species.

- Biodiversity benefits could not be quantified due to the extreme paucity of currently published relevant information.
- Overall, there is a solid case for the integration of alien tree management into policy formulation to increase water security in the dryland states of India, as well as in other arid and semi-arid global areas sharing common challenges.

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Author contribution

This paper is the sole work of the author, with support for fieldwork acknowledged where appropriate.

Author information

Raw data sheets (hand-written and transcribed into Excel files) are held confidentially by the author but can be made available to other researchers, with summary data and a sample field survey sheet uploaded as Supplementary Material C. The Author has no competing interests, and is also the corresponding author.

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Supplementary information

Three Supplementary Material files are uploaded with this contribution, as indicated in the text of the main paper:

- Supplementary Material A: Literature review concerning water used by eucalypts and neem trees in Indian drylands;
- Supplementary Material B: Literature review concerning ecosystem services provided by eucalypts and neem trees in Indian drylands; and
- Supplementary Material C: Spreadsheet containing summary data on water surveyed villages, including a sample field survey sheet.

Table
Click here to download Table: STOTEN#2 Table 1 - Relevant features of dryland villages (2019-11-07).docx

Table 1: Relevant features of dryland villages surveyed in this study

Village name	**State**	**District**	**Annual District rainfall in mm [a]**	**Village population [b]**	**Number of households [c]**	**Number of eucalyptus trees [c]**
Atarna	Haryana	Faridabad	697.6	1,791	400	10,000 (mainly plantation)
Panhera Khurd	Haryana	Faridabad		3,346	357	0
Beelwari	Rajasthan	Jaipur Gram (rural)	577.2	2,948	700	800
Dwarapur	Rajasthan	Alwar	630.9	1,823	365	300
Kishori	Rajasthan	Alwar		3,429	350	100
Malutana	Rajasthan	Alwar		2,325	550	1,000
Mandapur	Rajasthan	Alwar		657	50	2,000
Ramgarh Village	Rajasthan	Alwar		13,529	2,000	300

Sources:

[a] https://data.gov.in/catalog/district-rainfall-normal-mm-monthly-seasonal-and-annual-data-period-1951-2000 (accessed 09th September 2019)

[b] Census of India, 2011: http://censusindia.gov.in/ (accessed 09th September 2019)

[c] Local informants (see Supplementary Material C)

Figure

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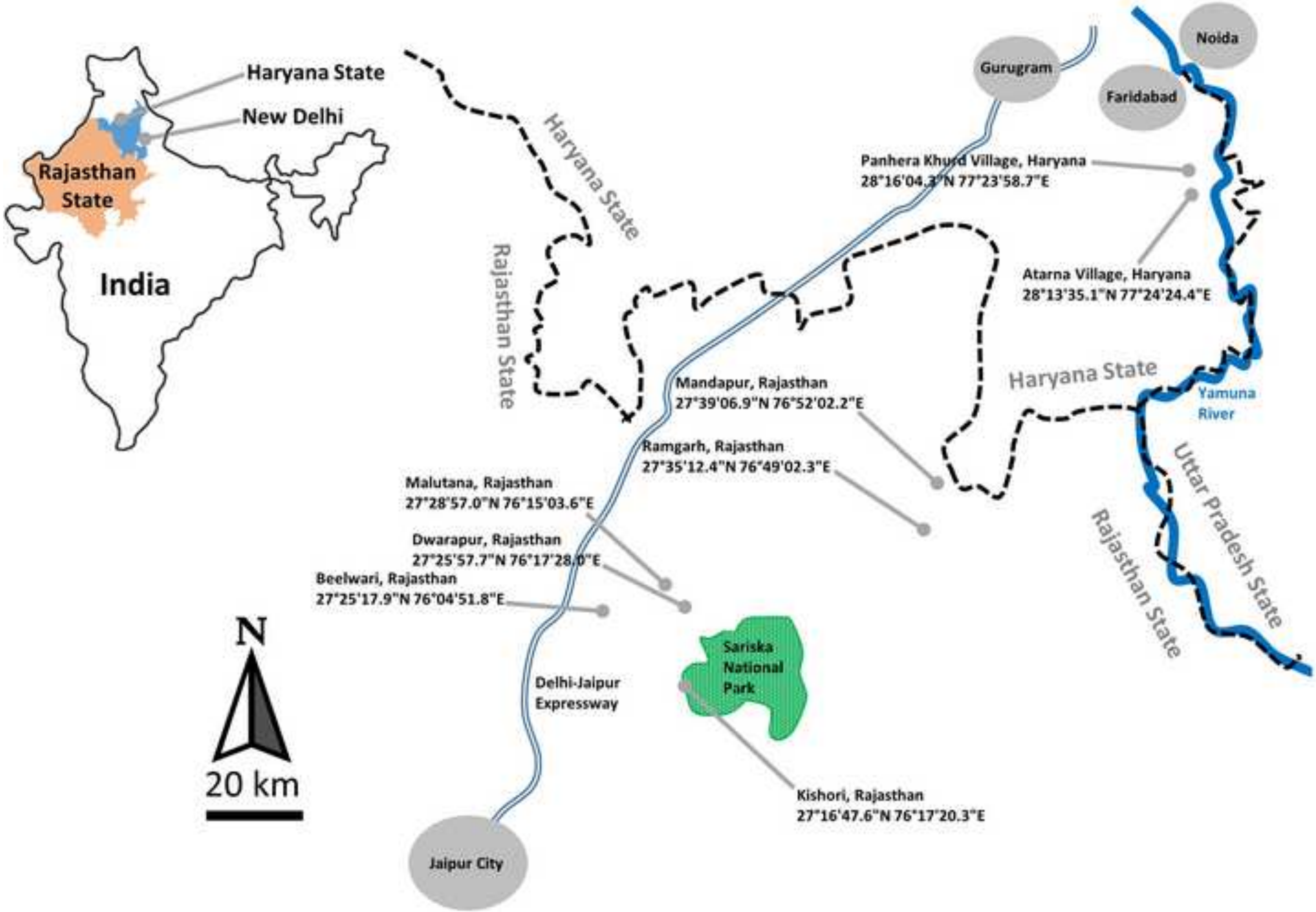
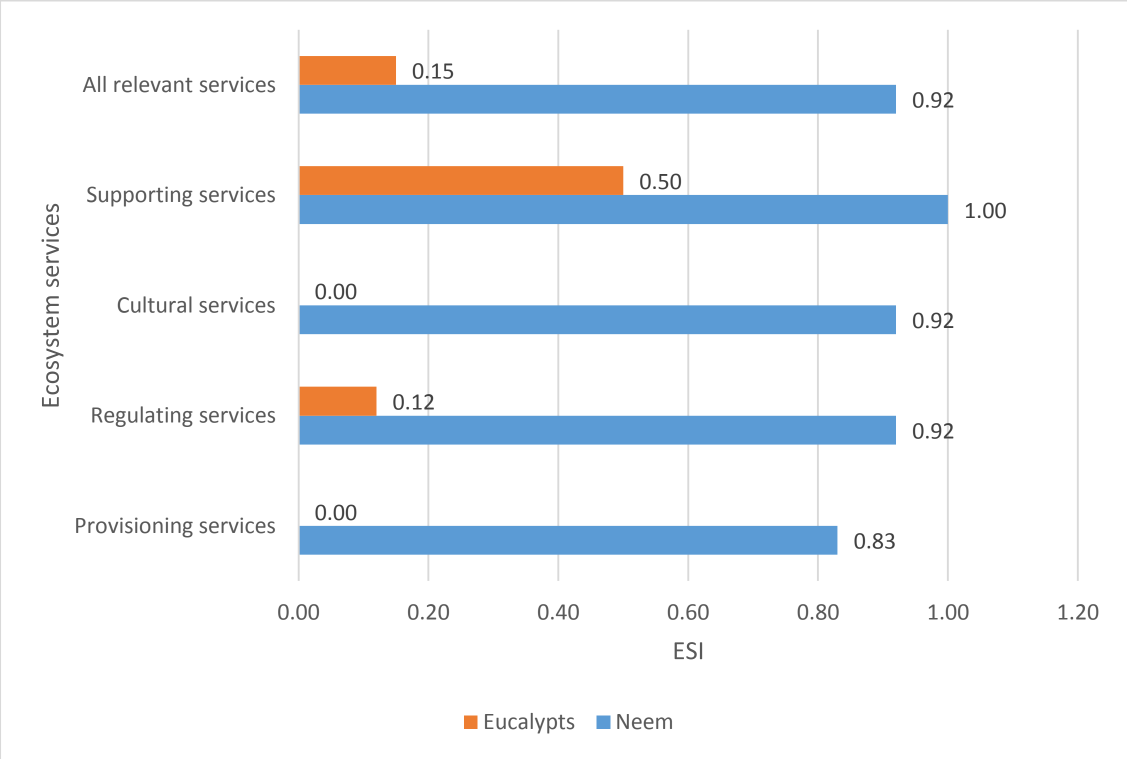


Figure

Click here to download Figure: Figure 2 - ESI scores for neem and eucalyptus.docx

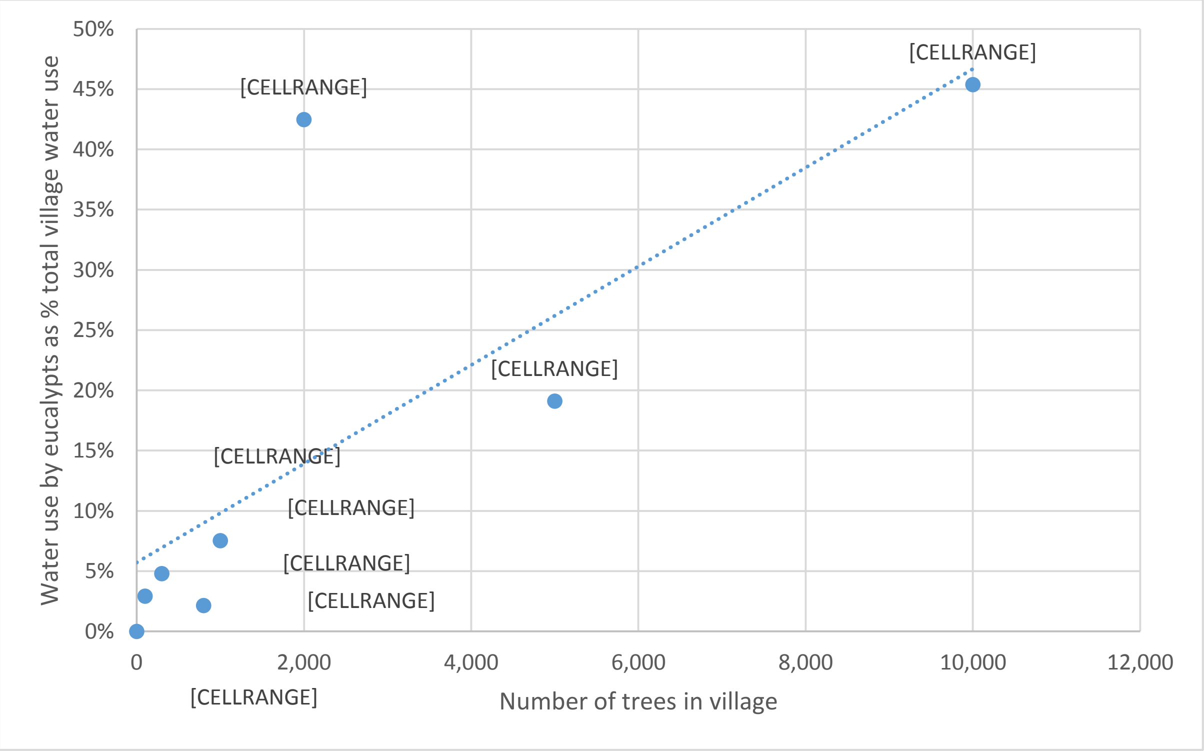
Figure 2: ESI scores for production of ecosystem services respectively by neem and eucalyptus



Figure

Click here to download Figure: Figure 3 - Water use by eucalypts as % total village water use.docx

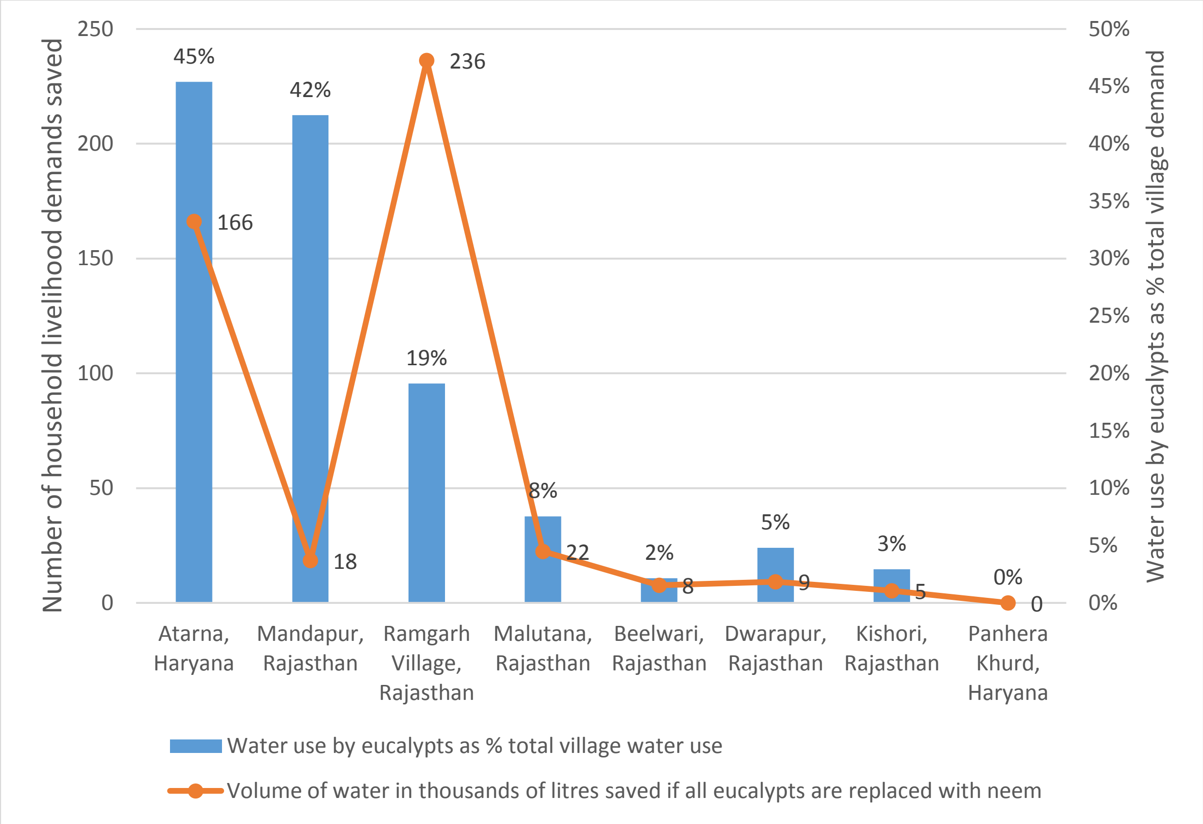
Figure 3: Water use by eucalypts as % total village water use, plotted against number of trees in each village (with approximate trend line)



Figure

Click here to download Figure: Figure 4 - Water use by eucalypts, amount of water saved.docx

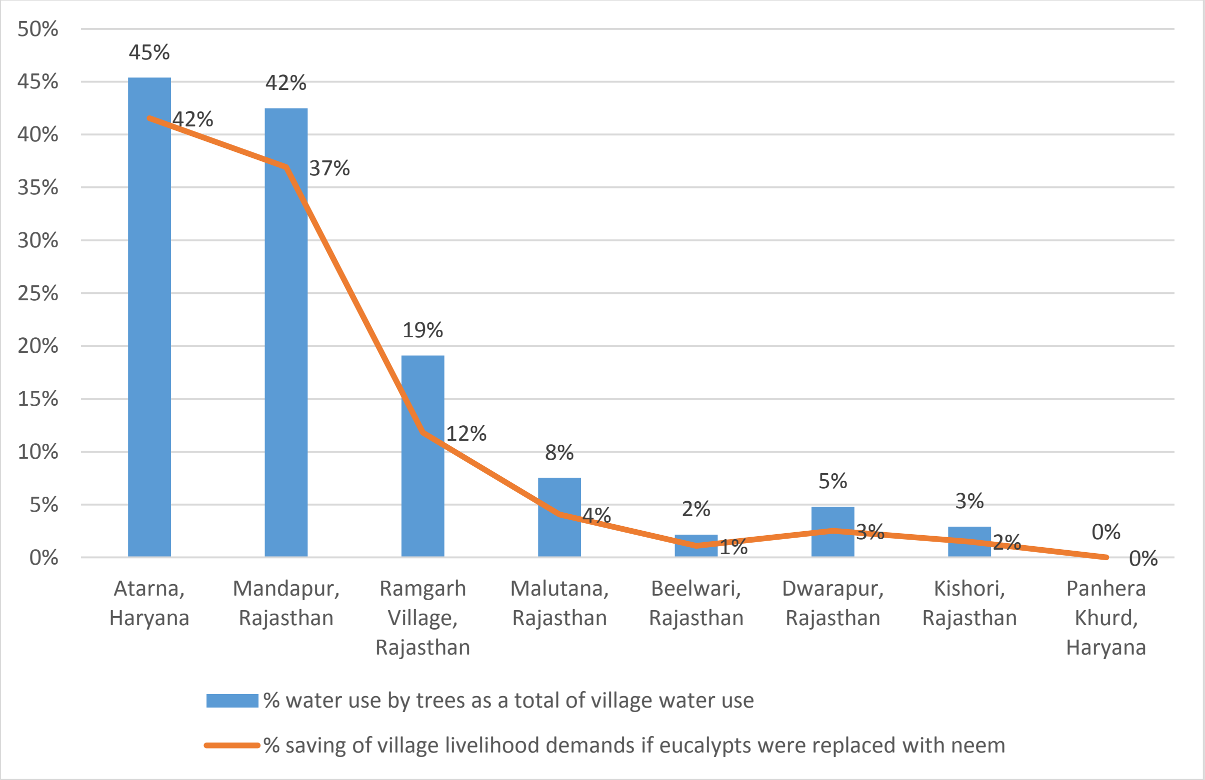
Figure 4: Water use by eucalypts as % total village water use, and amount of water saved if eucalypts are replaced with neem expressed as number of household livelihood demands



Figure

Click here to download Figure: Figure 5 - % saving of village livelihood demands.docx

Figure 5: Water use by eucalypts as % total of village water use, and % saving of village livelihood demands if all eucalypts were replaced with neem



Supplementary material for on-line publication only

Click here to download Supplementary material for on-line publication only: SuppB ESs for Eucalyptus and Neem CHANGES AC

Can management of 'thirsty' alien trees improve water security in semi-arid India?

CONFLICT OF INTEREST STATEMENT

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I have no conflict of interest.