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Agricultural water saving through technologies: a zombie idea

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Abstract: A zombie idea is one that has been repeatedly refuted by analysis and evidence, and should have died, but clings to life for reasons that are difficult to understand without further investigation. The perception that investments in modern irrigation systems automatically save water constitutes a zombie idea. On face value, most would accept that modernizing irrigation systems makes sense: agriculture represents 70% of global water withdrawals while physical irrigation efficiencies range between 25-50% worldwide—that is, most of the water entering the irrigation system never makes it to the targeted crop. However, the impacts of modern irrigation systems are complex, and as we show, usually have the opposite effect to that intended through altered cropping and water application decisions by farmers that aggravate water scarcity. This paper investigates how this zombie idea forms; why it persists, even when proven wrong by scientific evidence; and how to overcome it.

Introduction

If current water use patterns continue, global water demand will exceed the renewable supply by 40% in 2030, decreasing economic growth in water-stressed areas by 6% (2030 Water Resources Group, 2019). This is comparable to the 2020-2021 COVID-19-induced economic slowdown in the worst hit economies (IMF, 2020), but in the case of water scarcity the impact will continue into the future. Given that agriculture represents 70% of water demand and physical irrigation efficiency ranges between 25-50% worldwide—that is, most of the water entering the irrigation system (75-50%) never makes it to the crop—it is widely believed that modern irrigation technologies[1] can save significant amounts of water for other uses (FAO, 2021). This belief drives billions of dollars of public investments in modern irrigation technologies every year (Grafton et al., 2018), and is endorsed by the UN Sustainable Development Goal (SDG) 6, which calls for a "substantial increase in irrigation efficiency […] to address water scarcity" (UN, 2015).

This belief rarely aligns with wider scientific research and evidence. Global reviews on the performance of modern irrigation technologies show that these interventions usually result in greater consumption, not savings, due to altered cropping and water application decisions by farmers which aggravate scarcity (Pérez-Blanco et al., 2020). Thus, the assumption that modern irrigation technologies automatically save water is a zombie idea: one that has been thoroughly refuted by analysis and evidence, and should be dead, yet lives on for reasons that require further investigation (Krugman, 2020; Peters and Nagel, 2020; Quiggin, 2012). This paper investigates

[1] Including "sprinkler or drip irrigation systems, laser leveling of fields, piped delivery systems, canal lining, and rehabilitation of irrigation and delivery systems", as per the definition by Pérez-Blanco et al. (2020).

how this zombie idea is formed; why it persists, even when proven wrong by scientific evidence; and how to overcome it.

Why modern irrigation technologies aggravate water scarcity

All water entering an irrigation system goes to either: 1) productive consumption water that "is purposefully converted to water vapor, primarily crop transpiration"; 2) unproductive consumption water that is "not purposefully converted to vapor, such as through transpiration by weeds or evaporation"; 3) reusable return flow water "reaching a usable aquifer or stream with downstream demand"; and 4) non-reusable return flow water "flowing without benefit to a sink such as the sea, and therefore not usable" (Figure 1) (Pérez-Blanco et al., 2020).

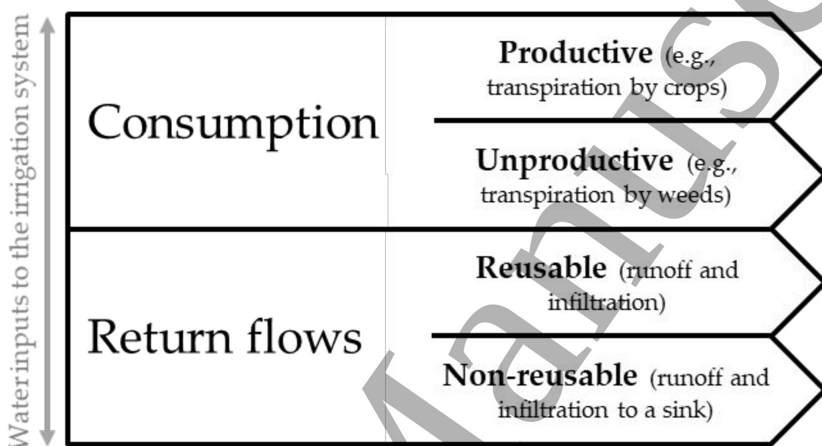
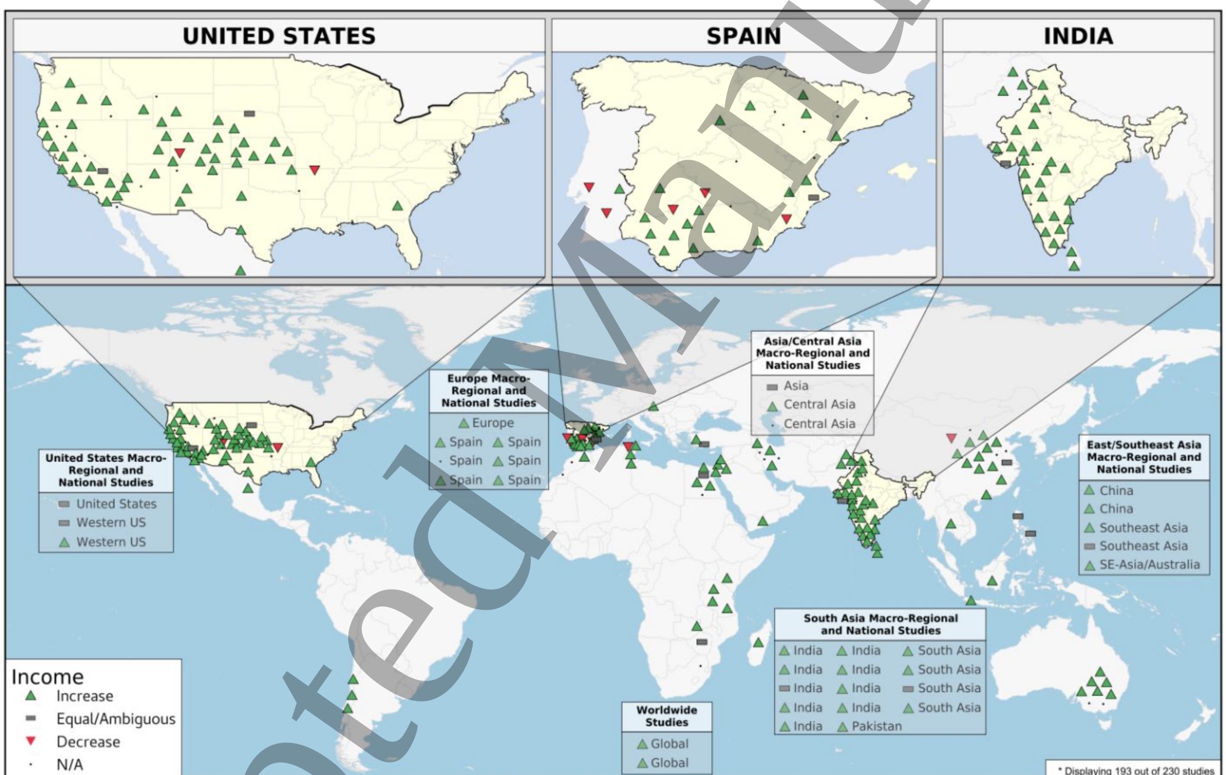


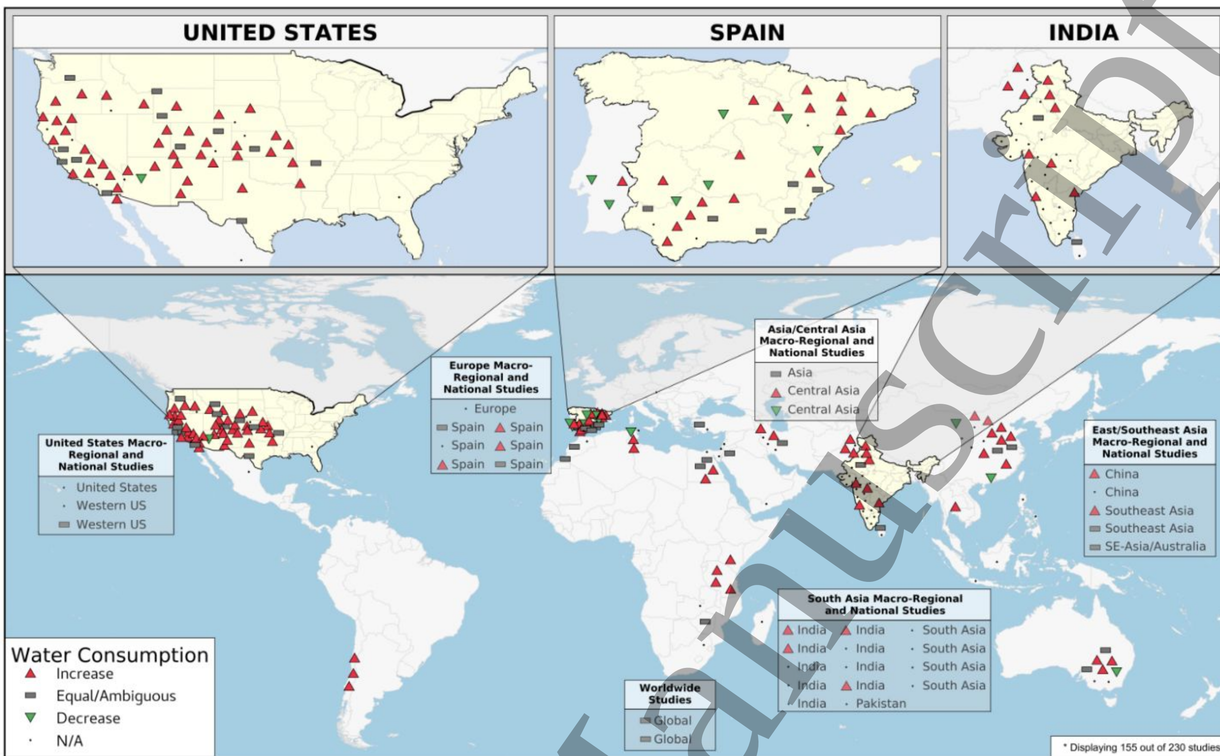
Figure 1. Water accounting schematic (mildly adapted from Pérez-Blanco et al. 2020). The logic set out in the figure is well illustrated by the example of modernized center-pivot systems and drip/sprinkler irrigation. In modernized center-pivot systems water is delivered close to the soil, avoiding unproductive consumption through evaporation from wet foliage and wind drift that carries irrigation water away from the crop. Thus, production can be maintained while delivering (and consuming) some 20% less water. If water input to the farm is reduced by 20%, a genuine water saving is achieved, and the saved water can be allocated to another purpose. On the other hand, if water input to the farm remains unchanged, the farmer can expand the irrigated area. In this scenario, no water is released to other uses (i.e., no saving), but production is enhanced without increased overall consumption (the increase in local consumption has no impact on other users because the "source" is unproductive consumption). In the case of flood irrigation conversions to drip or sprinkler, the water "saved" is more likely to be at the expense of return flows to aquifers or drains. If these are a source of water to other users, any local benefits are largely offset by negative impacts elsewhere. Equally importantly, in both cases the profitability of irrigating is increased and in consequence the farmer is incentivized to increase the quantity of water inputs as long as water is a scarce input—thus offsetting any potential savings.

Modern irrigation technologies are designed to increase the proportion of water input to the system that is consumed productively by crops. In principle, such modern irrigation technologies make it possible to keep agricultural output stable with the same volume of productive consumption, while achieving net savings through the reduction of unproductive consumption and non-reusable return flows. However, since modern irrigation technologies change the structure of costs and revenues experienced by farmers, it is unlikely they will act the same way after an intervention.

Following irrigation system conversions, more water intensive and/or sensitive crops can be produced with a higher revenue for the farmer. Revenue may also increase with the same crop if there is a strong yield response from additional consumption. Costs may decrease through reduced energy, labor and chemical input needs, or increase through higher operation costs (Grafton et al., 2018). Most available empirical evidence shows that adopting modern irrigation technologies generates additional revenue exceeding additional costs, incentivizing farmers to increase water consumption to elevate profits (Pérez-Blanco et al., 2020). The costs of conversion are often also subsidized, providing a wealth transfer to the farmer. Increased consumption will then: offset potential savings from foregone unproductive consumption and non-reusable return flows; grow at the expense of foregone reusable return flows; and reduce water availability elsewhere; while further complicating the water governance context (Figure 2).



(a)



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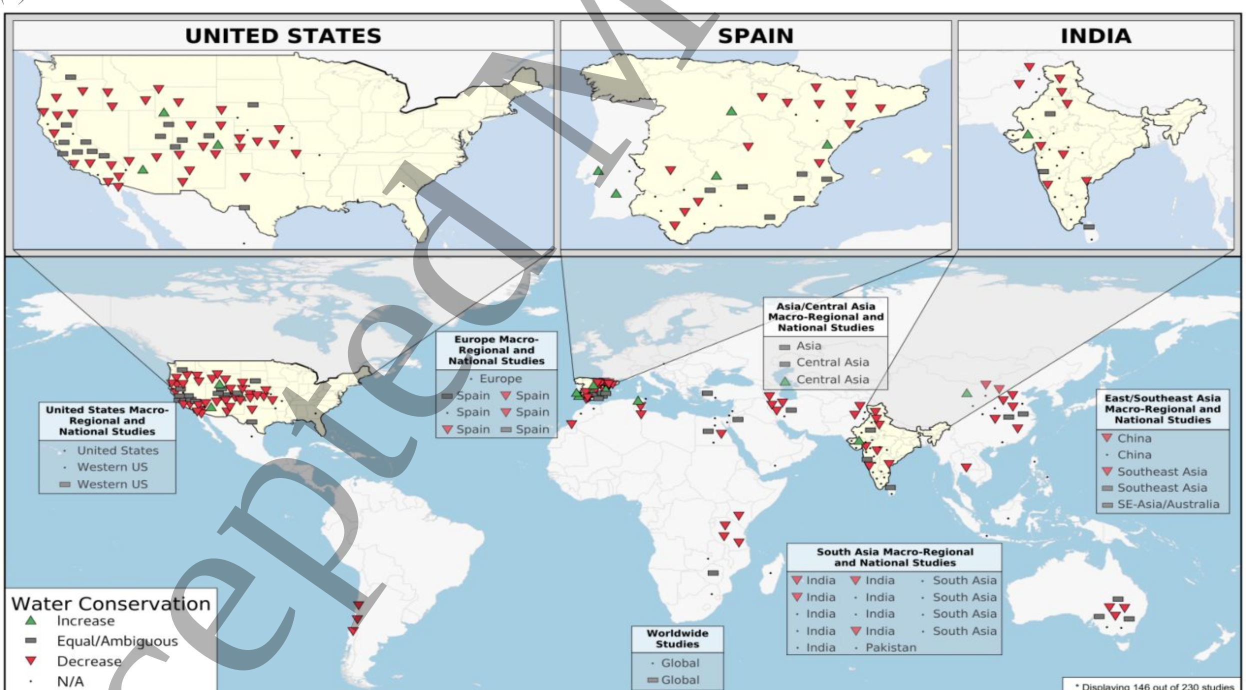

(c)

Figure 2. Impact of modern irrigation technologies on (a) adopters' income (measured through profit), (b) water consumption and (c) net water savings/water conservation, based on a global review of the empirical literature on farmers' responses to modern irrigation technologies (adapted from Pérez-Blanco et al. 2020). The criteria followed for the selection of papers in the review include: 1) the paper assesses the behavioral responses from decision units (farmers, groups of farmers, benevolent regulator); 2) the technologies considered include sprinkler

or drip irrigation systems, laser leveling of fields, piped delivery systems, canal lining, and rehabilitation of irrigation and delivery systems; 3) the paper reports the impacts of modern irrigation technologies on at least one of the following: profit, water consumption and net water savings. Results show that farmers typically use modern irrigation technologies to increase profit through higher productive crop consumption at the expense of unproductive consumption and (mostly) return flows. Under prevalent reusable return flow regimes (in our literature review, in 214 of the 230 case studies return flows are reusable), increasing productive consumption reduces water availability elsewhere (70.4% of the case studies). In those case studies where water is saved (11.2%), this is usually achieved through complementary quotas or charges that limit use; or where return flows are non-reusable and sufficient to accommodate growing consumptive demand, while reducing water inputs to the system. In the remaining case studies, net water savings do not change significantly (12.5%) or the results are ambiguous (5.9%). An account of the case studies and the database collected from them are available in Pérez-Blanco et al. (2020) and in the Annex.

The zombie idea of water-saving irrigation technologies: how it developed and why it persists

Krugman (2020), Quiggin (2012) and Peters and Nagel (2020) offer a set of six hypotheses (H) explaining the emergence and persistence of zombie ideas including: beliefs; path dependency; incentives; politics and power; information gaps and filtering; and the absence of alternative ideas. We adapt these six hypotheses to create a framework for assessing zombie ideas in the water efficiency context (see *Methods* in the online supplementary material). Building on this framework via case studies we assess how/why different players in the water policy arena have contributed to create and keep the water efficiency zombie idea alive. This approach enables us to provide key resources for understanding and treating the current zombie in water policy design and implementation.

H_1: Beliefs

The capacity of individuals to adequately process available data to make rational choices is "limited by the tractability of the decision problem, the cognitive limitations of the mind, and time constraints" (i.e. bounded rationality) (Simon, 1955). To address this limitation within complicated contexts, decision-makers (including those in watershed and donor organizations) have developed heuristic methods that reduce the difficult task of thoroughly assessing complex human-water systems to simpler judgmental operations (Tversky and Kahneman, 1974). Although heuristics are typically useful, they can also lead to systematic deviations from rationality in judgement—or cognitive biases (Morewedge and Kahneman, 2010). In the water sector, where socioeconomic aspects are under-researched and decision-makers and technical staff typically have a training in engineering and agronomy, cognitive biases often arise from an oversimplistic conceptualization of human agency (Pande and Sivapalan, 2017). This is the case of modern irrigation technologies, where presumed water savings are typically obtained based on 'scaling up' local measurements, i.e. multiplying the water saving estimates obtained in field experiments by the number of hectares modernized. This inductive reasoning ignores the behavioral foundation for farmers who opt for altered cropping and water application to crops. It also fails to appreciate that "losses" at one scale are often sources at another through return flows. The repeated adoption of modern irrigation technologies on the basis of these heuristics leads to a hypothesis of causality and the causal belief that modern irrigation technologies save water (Begg et al., 1992; Béland and Cox, 2011). Once the belief has been established, individuals and groups of individuals are more likely to accept (or even build) arguments that conform to that belief (Janis, 1971; Nickerson, 1998; Shermer, 2011), despite more recent information which discredits those arguments (Johnson and Seifert, 1994). This process is visible in donor "flagship reports" that are widely read and cited in the press. Such reports are necessarily broad-brush, but sometimes disturbingly casual in their acceptance of the fundamental assumption that modern irrigation technologies save water. A recent World Bank report addressing water scarcity (Damania et al., 2017) originally contained the following statement:

> *Studies show that advanced irrigation technologies, such as subsurface drip irrigation and micro-irrigation, can substantially improve crop yields* ***while reducing total water consumption*** *(Ayars, Fulton, and Taylor 2015)* [emphasis added].

This prompted the first author of the single citation (Ayars et al., 2015) on which this important assertion was based to object to the World Bank that his research reported reductions in *water applied* (i.e., water inputs to the system) not water consumed (Ayars, 2019). The report was duly revised, omitting the final phrase, but failing to add the crucial qualifier that a cursory review of the literature would have revealed—that increases in yield are typically associated with an increase in water consumption and aggravated scarcity. An earlier World Bank flagship report (World Bank, 2016) also promised savings from modern irrigation technologies, again relying on a single citation that explicitly noted that reported "savings" were in terms of water applied (Mushtaq et al., 2009).

H_2: Path dependence/lock-in

Large-scale public incentives and programs to modernize irrigation systems can lock-in choices for irrigation improvements "through a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale" at different levels (scale economies, learning economies, adaptive expectations and network economies) (Garrick, 2015). Escaping lock-in usually involves nested governance institutions accepting the evidence and investing in significant transaction costs, namely the resources used to change institutions and organizations towards the adoption of alternative water management instruments that effectively address water scarcity. Therefore, while institutional awareness and explicit recognition of the increased consumption and aggravated scarcity caused by the zombie idea is a necessary first step, it may be insufficient on its own to shift the policy focus away from modern irrigation technologies. Information gaps or opposition to reform by groups with vested interests can increase transaction costs, prevent institutional reform and favor the status quo (Garrick, 2015).

H_3: Incentives

Water scarcity and environmental damage more generally are exacerbated when economic incentives promote responses such as using more water than available, and obtaining private benefits while transferring costs to third parties (externalities) (Laffont and Tirole, 1991). Many players in the water policy arena face incentives to endorse the zombie idea:

- *Farmers* benefit from higher water consumption and profit while securing subsidies justified by the assumed benefits of saving water for others.

Farmers are individuals who seek to maximize their profit (proxy value for utility), subject to a series of constraints (e.g., water availability) (Pérez-Blanco et al., 2020). The limited capacity of farmers to invest in modern irrigation infrastructure is often quoted as binding constraint on the expansion of agriculture in water scarce areas, which otherwise enjoy several competitive advantages for irrigation (abundant, cheap land and labor, high solar radiation and proximity to high demand markets) (Damania et al., 2017). Public investments release the financial constraint to modernizing irrigation, thus loosening water limits for adopting farmers who can decide to increase the irrigated area and water consumption, yield and profit. Rarely are the true costs of developing water resources paid by those who access them, nor do they compensate for the externalities they create.

However, the higher local water consumption and profit is typically achieved at the expense of reduced water availability downstream (see Figure 2). Downstream farmers, made even more water-scarce by the increased upstream consumption, are then motivated to follow upstream adopters to maintain their water consumption levels despite the reduced return flows reaching their farms. This technology diffusion process (Balmann, 1997) further compounds the reduction in water availability for other users downstream (including both the environment and other farmers whose water supply is severely curtailed).

- *Equipment suppliers* benefit from increased prices, sales and profits.

The diffusion of modern irrigation technologies and the subsidies provided by the public sector towards their adoption shift demand for the products of equipment suppliers rightwards, increasing their profit. This gives manufacturers incentives to allege merits of their products, so that more farmers engage in irrigation modernization, more subsidies are provided by government, and prices, sales and profit are enhanced.

- *Regional communities* in the watershed surrounding adopters benefit from higher agricultural demand (e.g. labor, fertilizer) and production that drives economic growth through second-round effects.

By providing supplementary moisture, modern irrigation technologies have the ability to transform agriculture towards a higher input (labor, production chemicals, etc.), and higher output production system (e.g. perennials). This agricultural transformation will amplify economic growth through second-round effects (e.g. agroindustry), and attract population and infrastructure (e.g. schools, hospitals) (Parrado et al., 2020). Additionally, it is claimed, 'water savings' will drought-proof the community and prevent the large-scale fluctuation in income (both farm and non-farm) that occurs during droughts.

The reality is starker as the gains in technical efficiency brought on by a subsidy to reward modern irrigation technologies typically contribute to reduced overall economic efficiency by encouraging a misallocation of resources. That is, the subsidy has the effect of reducing total economic welfare summed over all sectors and time periods. This is evidenced in Australia's Murray-Darling Basin where water buybacks for environmental flows were initially abandoned in favor of subsidized conversions to modern irrigation systems, which have also been recently abandoned after a finding of no savings from modern irrigation systems—as predicted by scientists (Australian Parliament, 2017). This occurs because the increase in farm profit brought on by subsidies to convert to modern irrigation technologies is more than offset by other users' and sectors' economic losses added to the cost of the subsidy itself (Adamson and Loch, 2018; Ward and Pulido-Velazquez, 2008). Moreover, the transformation towards a high-input, high-output irrigation system places a greater quantum of private capital at risk (capital investment in modern irrigation systems is greater than in traditional irrigation systems or dryland activities) and this risk is amplified if the transition is towards perennial crops that will die when minimum water requirements are not met. As shown again in the Australian context, this can lead to non-trivial capital losses, default on loans and eventual farm exit—which are also amplified through second-round effects (Loch et al., 2019). However, while the benefits to adopters are easily observable following the uptake of modern irrigation systems, costs to third parties are often hidden and/or lie in the future—as seen in the example of return flow reductions from the cannibalization of resources by upstream users in Australia (Loch et al., 2020) or Spain (Lecina et al., 2010).

- *Donor organizations* (country aid agencies and international organizations such as the World Bank, the Asian Development Bank or the EU) can support projects that are capital intensive and politically inexpensive, rather than reforms that are politically costly—involving reducing supplies of water to existing users—and require little capital investment.

For donors, whose primary "product" is funding for development projects, notional water "saving" based on the zombie idea is more convenient and acceptable to recipients, while confirmation of actual impacts on water balances are rarely documented (Asian Development Bank, 2017; World Bank, 2017).

- *Decision makers* protect their political legitimacy by avoiding the difficulties (profit-loss, inequity) of direct interventions to reduce water allocations.

Political legitimacy arises from the attitudes and beliefs of citizens as well as the social and political context in which they have saliency (Rawls, 1999). Thus, it is only natural for those in authority to align public investments with those beliefs that strengthen their political legitimacy. Costly modern irrigation technology investments fit especially well into this space. They are seen as mechanisms to increase income in farming communities, benefit equipment suppliers with much to gain from technology sales, and may justify large-scale funding sources from donor organizations. Leveraging further on the zombie idea, modern irrigation technologies can also be promoted as an environmentally friendly and risk-reducing approach, where promised savings offer benefit to all under general perceptions of positive outcomes from reduced consumption or use. This often fails to properly account for negative externalities under over-simplified assumptions about the hydrological, economic, and institutional complexities of water management.

H_4: Politics and power

At a basin level, the fragmentation of power structures and their unequal influence means that negotiations often take place between powerful political actors, which are typically those who benefit most from the adoption of modern irrigation technologies (e.g., farmers), while those negatively affected are excluded (e.g., the environment, farmers lacking formal water rights that protect historical use) (Tanouti and Molle, 2013). This leads to a process of rent-seeking, where adopters appropriate wealth originally belonging to third parties (Tullock, 1967). Opportunities for rent-seeking increase incentives for regulatory capture across farmers and others who benefit (equipment suppliers) (Laffont and Tirole, 1991). Capture will occur where benefitted individuals increase their own capacity to co-opt those in authority to serve their interests—typically through lobbying and corporatism (Lopipero et al., 2007; Wiarda, 1996), where damage to the public interest is often covered up through misinformation (Lewandowsky et al., 2012). Thus, decision-makers may (and often will) argue that state or national interests can be met from irrigation efficiency improvements which offer the advantage of lessening the impact of any rent-seeking and regulatory capture claims and, along with such claims, potential threats to their political legitimacy from powerful lobbying groups such as farmers. Once this argument has been made, there are incentives for decision-makers (and donors) to "oversell" the policy; even more where results are ambiguous or negative, as it is being legitimated by legislatures (Peters and Nagel, 2020). In an example of misinformation, an inquiry into water use efficiency in Australian agriculture attracted many contributions, including the following by Netafim (Israel) (Netafim, 2017):

> *[T]he international Sustainable Agriculture Initiative (SAI) states "Drip irrigation remains without any doubt the most efficient irrigation technique and most powerful solution towards improving water productivity and ensuring food security"*

The above quotation omitted the rest of the sentence in the original SAI report (SAI, 2012):

> *... but due to the popular confusion in water accounting terminology, reports on efficiency gains have to be looked at carefully. It is thus important to always carefully assess what potential impacts the introduction of drip irrigation and planned increase of local crop production have on the overall water availability at watershed scale and the water flows left to other water users in the basin.*

H_5: Information gaps and filtering

The comprehensive expertise, research and costs for producing *ad-hoc* ex-ante assessments of irrigation modernization projects often mean that the relevant local data for an informed decision may be missing or unavailable. On top of that, decision-makers and donor organizations supervising and funding irrigation modernization projects may not have been vigilant in the implementation of adequate ex-post project assessments (Asian Development Bank, 2017; World Bank, 2017). Finally, although there is overwhelming scientific research and evidence showing that modern irrigation technologies increase water consumption (see Figure 2), this is not always effectively communicated (Pérez-Blanco et al., 2020). Further, transformational interventions with uncertain outcomes (e.g., market reallocations) may motivate a fear of the unknown, and thus hold little appeal for risk averse decision-makers (Kosovac and Davidson, 2020). In fact, some of these alternative interventions may not be even considered, since the filtering devices that are crucial to minimize decision-making costs can also limit the range of policies assessed (Peters and Nagel, 2020). Thus, we encounter one of the paradoxes of policymaking, where the filtering mechanisms that are necessary to limit the range of information and keep the problem tractable for boundedly rational decision-makers can also exclude potentially relevant interventions and help perpetuate zombie ideas.

H_6: Limited alternatives

When individuals accept a zombie idea as true, they build a mental model with the zombie idea as part of it (Lewandowsky et al., 2012). If the zombie idea is proven wrong and individuals remember and accept the correction, a gap is left in their mental model. However, people often prefer an incorrect model to an incomplete model, and may return to the zombie idea in the absence of a better explanation (Johnson and Seifert, 1994). Thus, without coherent, wellformulated and well-communicated alternatives, the zombie idea will live on (Lewandowsky et al., 2012).

However, the process of devising alternative mental models and policies is time consuming and involves significant transaction costs, so trusting the zombie idea and investing in technology is politically expedient. Accordingly, alternative ideas very rarely emerge (Peters and Nagel, 2020).

Confronting the zombie idea that modern irrigation technologies save water

We propose a treatment consisting of five steps centered on debiasing, heuristics, policy, institutions and inoculation to put to rest the belief that modern irrigation conversions will automatically save water.

First, cognitive bias and misinformation must be reduced (*debiasing*) through effective collection, analysis and communication of evidence for water efficiency outcomes. One commonly used debiasing approach is Reference Class Forecasting where decision-makers are asked to: 1) identify a group (reference class) of past, comparable irrigation modernization projects; 2) use data from the reference class to establish a probability distribution for the variable that is being forecast (e.g. water consumption); and 3) "compare the proposed project with the reference class distribution in order to establish the most likely outcome" (Morewedge and Kahneman, 2010). Group learning interventions based on clear evidence and where individuals can observe others making decisions will increase debiasing effectiveness (Yoon et al., 2021); although repeated iterations may be necessary to ensure success. Importantly for our purposes, identifying and presenting the vested interests of the parties involved can undermine zombie ideas. Communication should be clear, concise, tailored to the audience's worldview and focused on empirical observations rather than overtly negating the zombie idea to avoid backfire effects (Lewandowsky et al., 2012). Beyond the obvious emphasis on decision-makers, debiasing should also target broad scientific disciplines to ensure the behavioral foundations underpinning increased water consumption are understood beyond economists who tend to dominate this space. For example, engineers (who are those typically involved in the assessment of modern irrigation technologies) should be included in discussions such that a broad scientific consensus is achieved, as the zombie idea tends to permeate within such groups. This will further boost debiasing efforts where perceived scientific consensus and agreement across disciplines increases public support for policy action (Lewandowsky et al., 2013).

Second, providing an alternative that replaces the previous mental models is needed to reduce the effects of cognitive bias and misinformation (Lewandowsky et al., 2012). Thus, guidance and a new set of clearly articulated and easy-to-understand methods and heuristic frameworks will be necessary to displace existing beliefs, so that new principles can be assumed. These include:

- A scientifically sound water accounting framework that designates the disposition of resources between productive/unproductive consumption and reusable/non-reusable return flows.
- A framework for the effective design of interventions, where policy (i.e. objectives to be met) and institutional (i.e. interventions, programs or legal instruments to regulate) levels should not directly influence operational decisions (i.e. decisions about input/output uses by firms) (Ciriacy-Wantrup and Bishop, 1975). For example, instead of driving farmers

towards modern irrigation technologies we could set ecological flows (policy) to be met through quotas (institution) on total allocations that farmers would have to accommodate through changes to water inputs and technology (operationalization).

- A framework for the management of tradeoffs based on the theory of economic policy, which states that achieving a number of policy objectives needs an equal number of interventions (Tinbergen, 1952). Thus, if the objective of modern irrigation systems is to save water (target 1) while protecting rural income (target 2), two interventions are necessary—one for each target. By contrast, subsidizing modern irrigation conversions typically seeks to protect rural income *and* save water (i.e., one intervention, two policy objectives).
- A framework for robust decision-making such as that provided by the *Society for Decision Making Under Deep Uncertainty* (Marchau et al., 2019) which acknowledges, samples and manages uncertainty. Application of uncertainty sampling to modern irrigation technologies will reveal how loss of flexibility through higher consumption often tests systems to breaking point and irreversible losses (e.g., perennial crop forfeiture), thus contravening common water management goals under increasing future uncertainty.

Third, institutions and policy must be reformed to design incentives and behavioral change towards socially beneficial outcomes in support of the alternatives proposed above. Important steps include:

- Closed basins should specify a cap on withdrawals and/or consumption (depending on how allocations are defined—see below) from economic uses. Allocations should be defined as shares of this cap, for approved and site-specific uses.
- A centralized public accounting of all water allocations across the entire river basin, including information on the consumed fraction, should be introduced, leveraging on cutting-edge remote sensing data and methods (FAO, 2020).
- To avoid rent-seeking and regulatory capture by equipment suppliers/farmers who invest in modern irrigation technologies, allocations must be defined either i) as consumption entitlements or ii) as withdrawal entitlements that require periodic reductions as the consumed fraction increases.
- Environmental uses must be given legal security and actively enforced. This will strengthen opposition to the modern irrigation systems from economic users negatively affected by them (instead of encouraging technology diffusion at the expense of the environment/public wealth transfers).
- Subsidies to modernize irrigation technologies must be removed and replaced by sanctions for users who increase consumption at the expense of other appropriators (Ostrom, 2009).
- Auditing and incentive mechanisms that impose a cost on decision-makers who fail to act in the public good are required (e.g., limited access to donors' funding or sanctions as above).

Gathering data on spatial transaction costs over time from early on in this process can help identify and evaluate reforms that were successful in changing the trajectory of water institutions toward sustainability, illustrate the common drivers, and inform the development of reforms that overcome lock-in elsewhere (Garrick, 2015).

The general recommendations for policy and institutional reform above will need to be substantiated by site-specific research. There is a significant body of literature that studies institutional and policy reform roadmaps to incentivize and implement transformational adaptation towards sustainable and inclusive growth (see e.g., Gómez et al., 2017; Grafton et al., 2018; Loch et al., 2020). A common finding from this research is that to achieve water savings, modern irrigation technologies need to be complemented (if not substituted) with water reallocation policies that address the behavioral responses from water users driving consumption upwards, such as quotas, charges or buyback programs. This is aligned with the findings from our literature review in Figure 2, where in those case studies where savings were reported this was largely attributed to the presence of complementary quotas or charges that limited water use.

Fourth, future opportunity for change will most likely stem from shocks (e.g., climate change impacts or drastic reductions in water supply) where technology and the long lead-times associated with technology adoption and benefits will not provide appropriate solutions. It is therefore imperative to be ready with the policy and institutional alternative and roadmap, such that opportunities for change in response to shock events can be capitalized upon (Wheeler et al., 2017).

Fifth, in an analogy to biological inoculation, research has shown that preemptively exposing people to a "weakened" version of the zombie idea (i.e., preventive debiasing) can confer cognitive resistance to it, thus reducing the likelihood and spread of future zombie outbreaks and the need for the treatment above (Cook et al., 2018).

Conclusion

Abandoning the zombie idea that conversions to modern irrigation technologies will save water is a prerequisite to achieving sustainable water and economic security. While modern irrigation technology can in certain cases protect and enhance *local* agricultural income, its general scope for damaging effects on water availability and economic production elsewhere through altered cropping and water application decisions by farmers remain a fact. Herein we have framed the hypotheses and characteristics surrounding zombie ideas to develop a set of treatment steps to weaken, displace and finally eradicate the water efficiency zombie idea. We conclude that if the objective is saving water, resources are better employed in researching and testing the feasibility and performance of transition pathways towards transformational institutions and policies that are effective in saving water (such as quotas or charges), rather than in subsidizing modern irrigation technologies that increase consumption and aggravate scarcity.

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