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REVIEW

Restoring soil health to reduce irrigation demand and buffer the impacts of drought

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Abstract Irrigation consumes three quarters of global water withdrawals each year. Strategies are needed to reduce irrigation water use, including increasing the efficiency of transfer methods and field application. Comprehensive restoration of soil health, specifically through organic matter amendments, can substantially reduce irrigation demand and increase crop yield. A program to restore severely degraded and desertified soils by incorporating coarse woodchips into the soil successfully increased rainfall capture and elevated soil moisture for several weeks between rainfall events at both Ningxia, north-west China and North Dakota, USA. With addition of fertilizer, woodchip incorporation further increased growth of wheat and alfalfa. Comprehensive soil health assessment of remnant grasslands was used to develop target reference soil profiles by which to guide restoration efforts. Given that most agricultural soils are degraded to some degree, soil health restoration can provide a powerful strategy toward achieving global food and water security.

Keywords drought, irrigation, restoration, soil health, woodchips

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1 Freshwater scarcity and irrigation demand

Expanding the use of irrigation has been proposed as one key solution to the pressing need for increasing food production by 70% above 2006 levels in the coming decades[1,2]. Only 17% of current crops are irrigated globally, yet these areas account for 40% of all crop production[3]. However, there are serious weaknesses in current irrigation practices that must be addressed first. Irrigation already consumes a very large percentage (70% on average) of the total 4500 km^3 of water withdrawn for human use from rivers, lakes and aquifers each year[4]. This usage directly competes with the critical need for public drinking-water supply. As evidence, four billion people currently experience water scarcity when evaluated on a monthly basis[5]. Irrigation is the largest consumer but there are other uses limiting freshwater availability such as industrial water diversions, wastewater treatment, thermoelectric power cooling, and aquaculture, with the end result that an estimated 80% of the global population are exposed to high risks to water security[6]. The underlying problem is that all of these different demands are being placed on the same river or aquifer by siloed, non-integrated institutions and stakeholders, without consideration of the cumulative impacts on the water resource itself.

Diversions to supply irrigation significantly impact ecosystems. Diverting from rivers greatly reduces total flow and capacity to dilute wastewater pollutants, both of which threaten fisheries. Overdraft of aquifers is less visible but lowers water tables, leading to subsidence and to drying of streams and wetlands. Serious groundwater overdraft threatens communities and ecosystems covering thousands of square kilometers in almost every continent[7]. All of these problems are exacerbated as the frequency and magnitude of droughts increase due to global warming[8]. One key solution lies in increasing irrigation efficiency, both in the process of water transfer from source to the fields and in field application methods. A second, potentially more powerful solution, lies in improving soil health.

A general assumption in all irrigation is that only 50% of water withdrawn from the source makes it to the crop. This is an unacceptably high rate of loss or waste but also provides a clear opportunity for increasing overall water availability. Transfer of water to the fields from a river or groundwater source is a major factor in water loss and is the most frequently neglected aspect in irrigation analyses. Most transfer occurs in extensive systems of canals. For example, irrigation canal and ditch systems extend for 110000 km in Egypt[9], 480 km across 100000 ha of the Coleambally Irrigation District, Australia[10] and 4540 km in the Durance River basin in France[11]. In most cases the canals are essentially large trenches dug into the raw soil and this allows considerable evaporation, but as most are unlined there can be as much as 70% loss to deep percolation before the water reaches the field[12]. Lining the canals is an obvious solution but has been surprisingly slow in implementation. For example, the 132-km-long All American Canal has delivered water from the Colorado River through southern US deserts to California's Imperial Valley agricultural system since the 1940s. The canal is open to evaporation and was completely unlined for 70 years until 2009 when lining was completed for just 23 km of the canal. This became a controversial action because of the reduction in leaching and recharge to groundwater which had become a reliable source of water moving subsurface across the border and supplying wetlands in Mexico. The other major source of water loss is associated with the type of field application that is used. The three general methods of field application are gravity, sprinkler and trickle irrigation. The three types sequentially increase the efficiency of water delivery to the crop but simultaneously require increasing amounts of equipment, technological expertise and electricity, which translates to exponential increases in the cost of production. This expenditure becomes prohibitive for most small farmers in both developed and developing countries, and therefore adoption is unlikely without subsidies. It is clear that a comprehensive effort to increase irrigation efficiencies and reduce water transfer loss in all countries would free up large volumes of water for either public use or agricultural expansion. However, regardless of the field irrigation system used, improving the health of the soil, and specifically its capacity to store water, can greatly reduce the irrigation demand.

2 Agricultural soil degradation and plant water availability

Throughout history agriculture around the globe has been developed on grasslands which generally had fertile silty loam soils and exceptionally high ability to capture and store rainwater due to high soil organic matter content. Grasslands, broadly including prairies, steppes, and savannahs, formerly occupied about 40% of the global land surface[13]. These (not forests) were the predominant biome in semiarid regions receiving $<$ 500 mm of rainfall annually because grasses evolved multiple strategies for thriving under scarce and infrequent rainfall[14]. A key factor in temperate grasslands is the development of deep organic soils formed by the slow decay of leaves and roots over centuries, and regionally referred to as Mollisols (USA), chernozems (Russia), and black soils (China). These properties fostered highly productive systems that supported millions of antelope, bison or other grazers and complex food webs without supplementary irrigation.

However, for centuries to millennia, grasslands have systematically been replaced by agriculture. Current estimates are that 90% of the global grasslands have been converted, either for growing crops (1.53 Gha) or for pasturing livestock (3.38 Gha)[15]. Unfortunately, chronically poor agricultural practices have resulted in serious degradation of these grassland soils[16]. Clearing away grasses and tilling of the soil broke up the roots which held the soil in place, leaving it vulnerable to erosion. Overgrazing by livestock similarly removed foliage, leading to declining root biomass and rangeland degradation. Storms washed away organic and mineral particles. Fine silt and clay particles were blown away in dust clouds, notoriously photographed during the Dust Bowl of the 1930s in the USA. Organic matter similarly eroded away, but also decomposed when tilled and exposed to sunlight and fluctuating temperatures. Cumulatively, it is estimated that 1.66 Gha of land have been impacted by erosion worldwide[17].

Degradation of soil health is the second major driver behind increasing irrigation demand and has been historically undervalued or overlooked. Although precipitation is the ultimate source of water for plants, most species require root access to a reliable source of soil moisture to power photosynthesis, transpiration, and growth. It is the capacity of soil to capture and then retain rainwater that determines how much is available to plants during dry periods between rainfall events. Plant available water is defined as the difference between the amount of water held when the soil is almost saturated at field capacity and the amount remaining at permanent wilting point (PWP), when moisture is held so tightly that plants can no longer access it. Available water holding capacity (AWHC), like plant available water, is determined by the combination of soil texture, i.e., the relative amounts of sand, silt and clay, and the organic matter content. Sandy soils have the lowest water holding capacities and silty loams have the highest. However, organic matter content plays a critical role. Based on hundreds of samples collected across the USA, Libohova[18] and colleagues determined that soil organic matter (SOM) contents ranged from 0 to 8%, and each 1% increase in SOM (weight/weight) was associated with a 1.5% increase in AWHC for sandy soils and 0.6% for silt loams or silt clay loams. Hudson[19] reported even higher rates of water retention with increasing SOM content. Given that conversion of grasslands to agriculture has resulted in declines in organic matter content to $<$ half the original levels of roughly 10%[20], decreased AWHC has been the overlooked consequence. Degradation of soils is now recognized as a serious problem, a key limiting factor in our capacity to grow food and requiring ever increasing amounts of irrigation and chemical fertilizers to continue cropping. Arguably, civilization has developed by mining away the fertility and water holding capacity of its soils. Barrett and Bevis[21] have elegantly demonstrated the cascading effects of degraded soil health, including loss of soil fertility and organic matter content, on declining crop yields and increasing human community impoverishment. In the final stages, desertification takes over with blowing sand dunes consuming the landscape, incapable of supporting human life, and once arable land is abandoned.

3 Restoring soil health through conservation agriculture

Restoring soil health is the key to addressing the interconnected issues of reducing irrigation water consumption and addressing food security. There is growing acknowledgment that soil condition needs to be evaluated from a holistic framework simultaneously evaluating physical, chemical, and biological properties[14]. Historical approaches have focused primarily on the chemical aspects of nutrient availability and pH, and most commonly, the amount of fertilizer needed to achieve high crop yields. This narrow focus is increasingly inadequate, masking while exacerbating the underlying systematic degradation. Measuring physical properties (e.g., texture, bulk density, and available water capacity) provides critical insights into soil porosity and other factors that determine how well rainwater can infiltrate and be stored in a soil. Most recently, scientists have become aware of the importance of evaluating microbiological health[22]. Subsurface microbial food webs are essential: bacterial biofilms and fungal hyphae help to stabilize microaggregates in soils that are critical in preventing erosion, mycorrhizal symbionts bond with plant roots and increase resilience to drought and access to nutrients, and complex microbial food webs control a diversity of plant pests. Direct indicators of soil microbial activity include microbial respiration rate, biomass, and enzyme concentrations. Genetic assays that estimate the relative abundance of different bacterial and fungal groups are increasingly available, but understanding of their relative importance remains limited. Arguably, the single best metric of overall soil health is organic matter content, given its multiple roles in increasing water storage, nutrient holding capacity and microbial activity. Taking all these aspects into account, soil health is now defined by USDA as “the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals and humans”. Comprehensive analysis of all three suites of properties provides a powerful diagnostic tool for assessing the health of soils and guiding remediation efforts. Detailed protocols for measuring the complete suites of physical, chemical, and biological indicators are available at Cornell University’s Soil Health website.

There is a well-researched tool kit of options within conservation agriculture available to address a diversity of site-specific soil problems such as excess acidity or alkalinity, trace metal toxicity due to mining, or soil pathogens impacting plant growth. However, the successful revitalization of comprehensive soil health in agricultural settings has been consistently linked to two main strategies: transition to reduced or no-till agriculture that minimizes soil disturbance, and use of organic matter amendments[22]. No-till agriculture is critical for allowing the soil to rest and heal, providing appropriate stable conditions necessary for the microbial ecosystems to rebuild the bacterial biofilms and fungal threads which connect and bind the soil together, and to resume the accumulation of organic matter. A comprehensive meta-analysis of 610 studies found that in dry climates, no-till agriculture can maintain or increase crop yields if implemented in combination with cover crops, leftover crop residues and crop rotations[23]. Ideally, in some settings, tillage should be eliminated altogether, and instead the planting of perennial grains or biofuel grasses will develop dense foliage with associated root mass[24]. Rodale Institute’s innovative roller crimper can bend the foliage of rye or vetch cover crops, permitting the planting of soybean and some vegetable crops without tillage. Where tillage is necessary, then the new Prairie Strip Practice (CP-43) in the USDA’s Conservation Reserve Program, which alternates 10-m-wide strips of perennial native prairie plantings with rows of crops, is proving to be a reasonable compromise with benefits for soil protection and pollinators[25].

The second critical solution for improving soil health is the use of organic matter amendments. The impacts on soil health are strongly dependent on the type and longevity of the amendment and whether the organic amendment is simply applied to the soil surface or incorporated deeper into the soil profile. Livestock or human manures have been applied throughout history to replace nutrients depleted by chronic harvesting, along with adding back some organic matter. Also, residues of maize, rice and wheat are frequently incorporated for similar benefits. Subsurface incorporation positively affects physical, chemical, and biological properties. However, surface mulching with either crop residues or woodchips is valuable in helping to maintain higher soil moisture content, reduce erosion and inhibit weed growth. Only after years of consistent surface application does mulch get integrated deeper into the soil profile[26]. A broad array of municipal wastes such as lawn clippings and leaves, and commercial wastes from food and paper industries, are now being evaluated for their use as organic matter amendments. Due to accessibility, aesthetics, and weed reduction, woodchip mulching has recently gained great popularity and bolstered the billion-dollar landscaping industry globally. Organic amendments arguably offer greater benefits than so called plastic mulches. These plastic sheets help reduce evaporative soil water loss, heat up the soil surface and, if transparent, can foster germination.

4 New approach of coarse woodchip amendment to increase rainfall capture and soil moisture content

More serious strategies are needed for the most severely degraded soils, soils consisting of over 90% pure sand, undetectable amounts of organic matter and limited nutrients. Characterized by blowing sand dunes and parched soils, these systems are labeled as desertified, but they are not true deserts. In many regions these systems still receive useful amounts of rainfall throughout the growing season. However, the soils have become too degraded to capture this water and it is rapidly lost through percolation or evaporation. As an international team of scientists, we have developed a new technique to add to the limited existing tool kit of strategies for restoring such desertified landscapes. For the past decade we have been testing and demonstrating the use of incorporated coarse woodchips as a strategy for jump-starting the restoration of severely degraded grassland soils.

The foundation of the method is to incorporate coarse woodchips, roughly 1–3 cm long, into the top 20–30 cm of the soil. The initial rationale for using coarse woodchips was due to their slower decomposition rate compared to the more commonly-used crop residues and manures. This would ensure that this organic matter would be present for several years thus allowing the soil sufficient time to recover. Through various replicated microcosm and field experiments conducted in Ningxia, China and in New York and North Dakota, USA we have consistently demonstrated that the woodchips capture higher amounts of rainfall and maintain higher soil moisture contents for several weeks compared to untreated control soils (Fig. 1). Increasing the concentrations of woodchips from 2% to 11% (vol/vol) was correlated with greater moisture retention[27]. Where field plots were irrigated, woodchip amendment reduced the total number of days below PWP throughout the growing season by as much as 30% when compared to unamended soils[28]. The greatest moisture retention occurred in plots where the incorporated woodchips were augmented with a thin branch shelter. These shelters consisted of thin willow branches stacked over the plots, about 30 cm high and intercepting about 50% of the sunlight. Each shelter helped to shade and cool the soil and also reduced evaporative losses by reducing wind speed. These benefits of all treatments remained four years after the initiation of the study.

We are integrating results from the various studies to determine the underlying mechanisms by which the

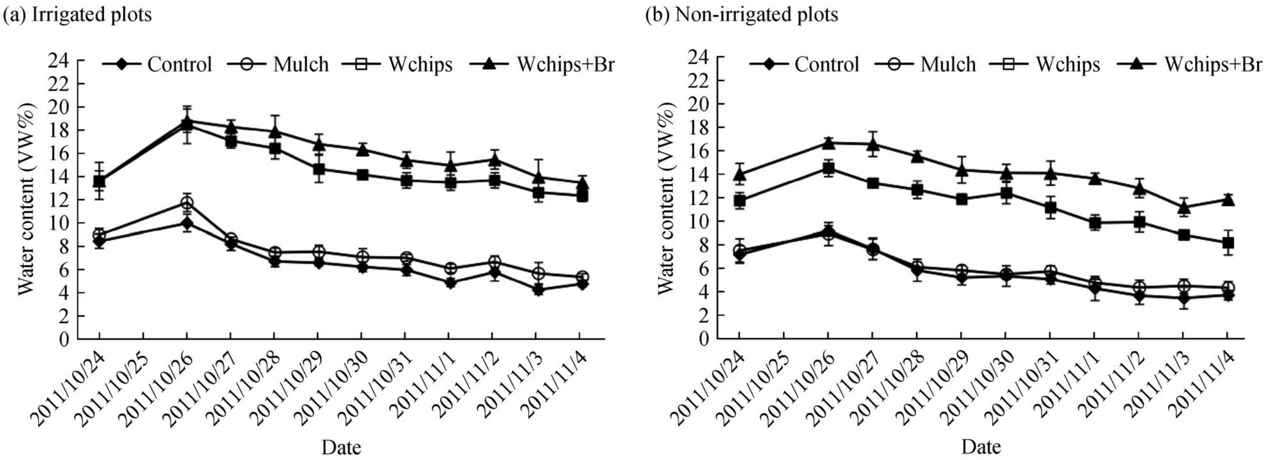

Fig. 1 Differences in patterns of volumetric soil water content between unamended soil (control) and three different treatments in adjacent irrigated (a) and non-irrigated (b) field plots, Ningxia, China (Mulch = surface-applied woodchips; Wchips = 5% woodchips incorporated into soil; Wchips + Br = incorporated woodchips plus branch shelter). See Li et al. for details of methods[27].

woodchips function in the soil profile, but numerous questions remain. A comparison of woodchips with nonporous rubber chips clearly demonstrated that the woodchips were absorbing water and then releasing it slowly back into the surrounding soil[29]. There was strong evidence that woodchip amendment alone can catalyze the development of a strong soil microbial community. Several metrics, including microbial biomass, respiration rate and enzyme activity were all significantly elevated in the woodchip-amended soils when compared to unamended soils, and diverse bacterial and fungal assemblages were present[27,28,30]. Notably, the treatment with only surface-applied woodchips did not increase microbial activity, even though soil moisture levels clearly increased (Fig. 1).

We conducted a series of experiments combining woodchip amendments with fertilizer. Given the extent of degradation of Ningxia soils, they are unable to support plant growth without supplementary nutrients, even with woodchip amendment. Alfalfa and wheat growth was significantly increased by nitrogen plus phosphorus fertilizer in woodchip-amended soil[27,28], whereas using only nitrogen fertilizer decreased the growth of buffalo grass in greenhouse experiments[31]. We hypothesize that rapid microbial uptake outcompetes plants for phosphorus when nitrogen is in excess, a finding supported by research on nitrogen immobilization in the restoration of Hungarian grasslands[32]. In the presence of the woodchips, adding liquid fertilizer produced lower concentrations and amounts of dissolved nitrate and phosphorus in leachate than dry fertilizer[29]. However, it is unclear whether the nutrients are being held by ion exchange processes on the surfaces of the woodchips or internally in pore spaces. We also conducted a pilot study evaluating the use of woodchips for supporting crops in highly salinized soils. When coupled with irrigation, saline soils heavily amended with woodchips produced a successful sunflower crop in five months. In contrast, there was almost no growth in the same irrigated soils without amendment (Fig. 2). The mechanisms remain unclear but this approach shows great potential for dealing with other regions impacted by soil salinization globally.

Our microcosm experiments compared a range of wood species and of manures, crop residues and biochars. Wood species worked better than the crop residues for water retention, and significantly better than manures[27]. Silver poplar (*Populus alba*) was the source of woodchips in the Ningxia field studies because of its local availability. This tree is planted along highways throughout China to facilitate erosion control and is therefore abundant and easily accessed. Its branches can also be pollarded, providing a continuous supply of wood. However, we recommend that every third tree along the highways be used for woodchips and replaced with a different tree species to foster more diversified and resilient roadside shelter belts. Wood species also differ greatly in their rates of decomposition[33]. There are potentially considerable benefits in using a combination of fast and slow decomposing woods in the woodchip amendment system. In particular, *Robinia pseudoacacia* (black locust) can last for a century undecomposed and provide long-lasting benefits.

We recommend growing shelter belts of mixed wood species alongside degraded farm fields as a source of actively growing wood for pollarding and transfer into the adjacent soils. This broad landscape approach to restoration, integrating shelter belts and soil restoration, can thereby provide the basis for carbon sequestration. Restoration of semiarid soils has been identified as a major solution in sequestering carbon, with the potential for sequestering as much as 2–3 $\mathrm{Gt \cdot yr^{-1}}$ C[34]. In China, the total potential of soil organic carbon sequestration in degraded soils was estimated at 105–198 $\mathrm{Tg \cdot yr^{-1}}$ C[35]. The initial woodchip amendment can act as a capital investment in the soil carbon pool, but the maximum rates of carbon sequestration will only happen if a diverse community of grass species are replanted[36]. Additionally, our pilot field studies demonstrated the great potential for restoring grasslands to support diverse wildlife. We had moss and mushrooms growing under the wood shelters

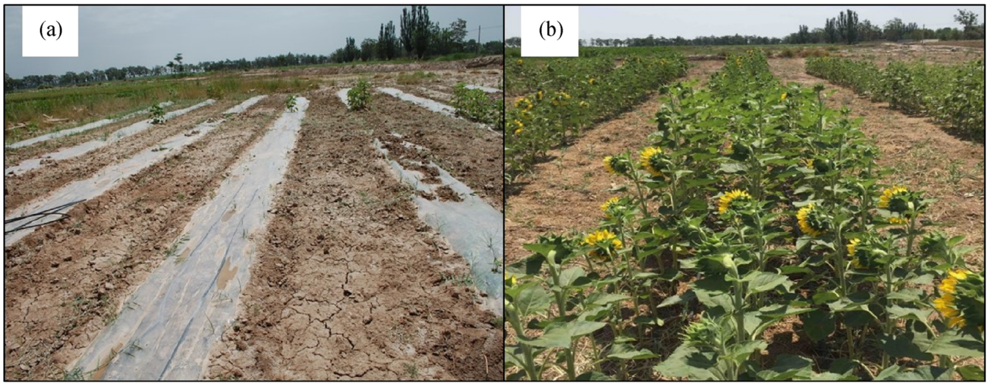

Fig. 2 Comparison of sunflower crop grown simultaneously in adjacent plots in saline soils, without woodchip amendment (a) and with woodchip amendment (b) in Pinlou, China (photos: ©Rebecca Schneider, June 21, 2016, 12:04 P.M.).

after one year, with subsequent colonization by lizards and hedgehogs.

Our current research efforts are investigating intact soil profiles from remnant or relict grasslands in order to develop an ideal, target soil profile to guide our restoration efforts. Remnants are pieces of the landscape that have escaped tillage and conversion to agriculture that have native plant communities and minimum soil surface erosion. However, given the global extent of grassland conversion to agriculture and centuries- to millennia-long time frames, there appear to be few or no remnants left in some regions. The few remnants remaining are generally found in reserves, cemeteries, or marginal lands. In these investigations we are using the comprehensive soil health analyses to quantify physical, chemical and biological properties of remnant soils. These diverse metrics characterizing the reference soil profile provide a powerful reference tool for diagnosing problems in nearby degraded systems. Our pilot investigation of remnants in the tallgrass prairies of eastern Nebraska, USA is clearly demonstrating that these remnants have higher organic matter contents, greater available water capacities and healthier microbial communities than adjacent farmland[37]. We plan to continue this effort throughout different grassland types across the Great Plains in order to develop a portfolio of remnant soil profiles representing a range of climates and soil types. These profiles should prove useful in guiding restoration in regions of similar climate and geology where no remnants remain. For example, the North-Central Grasslands of North and South Dakota, USA have similar climate and vegetation to Ningxia, China and remnant soil profiles may help guide restoration efforts there[38].

5 Conclusions

The use of coarse woodchip incorporation has great potential for addressing the issue of freshwater scarcity in the face of increasing droughts and global warming. Semiarid regions or drylands cumulatively receive $<$ 500 mm of annual rainfall, but this amount is concentrated during the growing season and typically delivered as small events of 1 cm or less every week, with much larger events of $>$ 30 mm scattered throughout the summer. Woodchip incorporation has been successful at capturing water from small rainfall events and maintaining higher soil moisture contents until the next event. We hypothesize that increasing concentrations of woodchips or incorporating them deeper into the soil profile will magnify this benefit by capturing water from the larger events as well. This strategy may be a key part of the solution to the changing climate in contexts where more high-intensity rainfall events alternate with longer, hotter dry periods, and may help to buffer the impacts of associated droughts. At a minimum, this strategy will help to reduce irrigation demand. However, if implemented across a broad range of landscapes, this new approach can simultaneously provide solutions to restoring desertified soils, expanding the capacity of degraded lands to produce food and help increase the availability of freshwater for public water supplies. Significant carbon sequestration is possible where agroecosystems combine shelter belt wood supply with soil restoration, especially if perennial grasses are allowed to establish. Promoting strips of native grassland species also supports pollinators which are critical for successful crop production. Restoration of degraded and desertified grassland soils is the key to our future and will provide a healthy, sustainable landscape for humans and wildlife.

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Compliance with ethics guidelines Rebecca Schneider, Stephen Morreale, Zhigang Li, Erin Menzies Pluer, Kirsten Kurtz, Xilu Ni, Cuiping Wang, Changxiao Li, and Harold Van Es declare that they have no conflicts of interest or financial conflicts to disclose.

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