Turning Soils into Sponges

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Union of Concerned Scientists

Appendix A: Methods and Experiments Included in the Infiltration Rate Meta-Analysis[1]

Rationale for Practice Selection

In this analysis, we focused on the principles of conservation agriculture as outlined in prior reviews and meta-analyses (Powlson et al. 2016; Pittlekow et al. 2015; Palm et al. 2014) which typically include: zero tillage practices that eliminate conventional tillage and associated soil disturbance (referred to as *no-till*); cover cropping or green manure practices that keep soils covered as compared to leaving them bare (*cover crops*); and diversified farming practices (including crop rotations and intercropping) as compared to monoculture cropping (*crop rotations*).We also assessed the impact of additional agricultural practices based on ecological principles, primarily perennially managed systems (including *agroforestry*, *perennial grasses*, and *managed forestry*), compared to annual cropping practices only (*perennials*). Finally, we looked at the case of cropland grazing (e.g., grazing crop residues or planted pasture grazing), as compared to conventionally harvested or hayed cultivated fields, to understand how this phase of integrated crop and livestock systems affects infiltration rates (*crop and livestock*).

Finally, in order to investigate the potential of different management practices on grass-based grazing systems, we searched for experiments that evaluated several different livestock grazing practices and measured infiltration rates. These practices included the impact of increased stocking complexity and reduced stocking rates or densities (*grazing management*) as well as the impact of strategically excluding livestock for some period of time (*grazing exclusion*).

Literature Search

The primary literature search was conducted using *EBSCO Discovery Service*™, which includes more than 23,000 publications from databases such as JSTOR and publishers such as Wiley, Elsevier, Springer-Nature, IOP, Royal Society, Oxford, Cambridge, Thomson Reuters, AAAS, and the American Society of Agronomy. The *EBSCO Discovery Service*™ matches on subject headings, keywords, and keywords in abstracts. The keyword strings for the crop analysis included "infiltration W1 rate" AND "crop*" for all searches and additional keywords are described below for each practice. For the grazing experiments, our keyword search included the terms "infiltration W1 rate" AND graz*". These keyword terms returned more than 800 possible studies to evaluate, of which 116 ultimately fit our criteria of experiments that had an appropriate experimental design (descriptions included by category) while also measuring water infiltration.

After the search with *EBSCO Discovery Service*™ was complete, we used the USDA-NRCS Soil Health Literature database to find additional research papers. This source is compiled by the NRCS Soil Health Division by searching databases such as Google Scholar to find peer-reviewed publications that categorize the impact of agricultural management on a range of soil properties (NRCS 2016). It is updated regularly by staff and includes more than 400 peer reviewed references (as of September 2016). The meta-data also note which experiments include information on infiltration rates. From this search, we added 10 additional studies for a total of 126 included in this analysis.

No-Till Experiments

Papers identified from the additional search term "till*" were included if experiments clearly included a no-till treatment. We did not compare reduced tillage to conventional tillage (as some no-till meta-analyses have done, e.g., van Kessel et al. 2014). However, when papers included multiple tillage practices that could have been counted as a control treatment, we included all comparisons in the dataset and classified them as conventional or reduced tillage based on the reported equipment and/or method of tillage.

[1] Adapted from Basche and DeLonge (n.d.) and DeLonge and Basche (n.d.).

Cover Crop Experiments

Papers identified from the additional search string of “cover crop*” OR “green manure” OR “catch crop*” were included when a control treatment with no cover crop was present (e.g., bare soil when the cash crop was not growing). Experiments were included when the cover crop was planted and grown intentionally to protect the soil and was not harvested, and residues were mechanically terminated, chemically terminated, or left as a green manure (e.g., a crop grown specifically for fertility purposes).

Crop Rotation Experiments

Papers identified from the additional search string of “rotation” AND “continuous” were included when there was a control treatment that represented the continuous cropping of one cash crop. The experimental treatment needed to include the same crop as well as at least one additional crop, grown in rotation, similar to the protocol utilized by McDaniel et al. (2014). We also included two experiments in which an additional crop was grown not as a rotation but as an intercrop (i.e., two different plant species grown simultaneously on the same field) and one experiment that met the crop rotation criteria but also included livestock grazing in the experiment treatment but not the control (Table 1). In all experiments, we recorded the number of crops included in the treatment cropping system for more detailed analysis.

Perennial Experiments

Papers identified from the additional search string of “perennial” OR “agroforest*” included experiments in which a perennial treatment was compared to a cultivated annual cropping treatment. In this category, we included experiments with a range of treatments, including perennial grasses, agroforestry and managed forestry (Table 1). Control treatments were all annual cropping systems, although they varied slightly by experiment (e.g., they included monocultures either with or without conventional tillage). Two of the eight experiments included in this category also included livestock grazing in the treatment (with an annual crop system with no livestock as a control; Table 1).

Crop and Livestock Experiments (Cropland Grazing)

Papers identified from the additional search string of “graz*” AND “livestock” were included if there was a crop-only control treatment (including pasture with cultivated forage crops) and an experimental treatment of similar crop systems with livestock grazing (of crop residues or forage), representative of one potential phase of integrated crop and livestock systems. This group included experiments with either annual crop or pasture-based systems, in which control treatments were harvested traditionally (i.e., with equipment) and were not grazed. These experiments differed from the three other experiments with livestock included in the study (one crop rotation and two perennial studies) in that the primary treatment in this case was livestock grazing versus traditional harvesting and not a change to a crop rotation or a switch from annual to perennial crop systems.

Improved Grazing and Livestock Exclusion

Papers identified from the keyword search of “graz*” AND “infiltration W1 rate” were grouped into the following categories:

Increased stocking complexity: Experiments were included in this category if they represented a switch from a continuous (year-round or seasonal) grazing pattern to a more complex or strategic managed system (Table 2). This primarily included stocking patterns changing from a continuously grazed system (year-round or seasonal) to systems managed using more complex strategies (e.g., rotational, mob, adaptive, etc.). We also searched for cases of increasing management complexity through variables, such as by moving from a fully grass-based system to silvopasture. However, we found only one paper (Sharrow 2007) that met those criteria. Although this category primarily included comparisons that added complexity while they kept stocking rates (ha AU^{-1} y^{-1}) very similar, there were three studies that did include a relatively high change in stocking rate (see Table 2); in two cases the increased complexity was combined with an increase in stocking rate (i.e., reduction in stocking pressure; Taddesse 2002; one site in Weltz 1986), whereas one case involved a decrease in stocking rate (Proffitt 1995).

Reduced stocking rates or densities: Treatments were included in this category if they represented a reduction in grazing pressure without any clear changes to grazing land management complexity (e.g., without switching from continuous to rotational grazing; see Table 3). Changes in grazing rates or densities were reported as a variety of variables or indices (stocking rate, stocking density, residual phytomass, or degradation/vegetation type).

Grazing exclusion: We found that numerous experiments from our search included treatments in which livestock were strategically excluded from grazing areas for a specified period. In fact, 58 percent (10/17) of the complexity studies and 88 percent (15/17) of the stocking rate studies included grazing exclosure measurements (Tables 2 through 4). Additionally, we identified 15 more studies from our keyword search that had measurements on exclosure, but did not fit into the other two categories. We therefore included this category for analysis to determine if there was an effect on infiltration rates from intentional livestock exclusion, defining the experimental treatment as the exclosure and the controls to be the grazed treatments (either continuous or complex). In most cases, grazing was excluded from an area that was previously grazed. We further categorized the exclosure treatments based on what type of grazing they were being protected from (complex vs. continuous, and a light, moderate, heavy, or very heavy stocking rate, as defined by the authors). Treatment duration was defined as the time since the exclosure was introduced; note that this was not always equivalent to the time since introduction of the grazing pattern that was represented by the control and, therefore, some of the grazing regimes in the controls should be considered only a proxy for the grazed condition.

Database Design

After experiments were determined to fit the criteria for study inclusion, key data were categorized in a systematic way. Many experiments reported both initial infiltration rates as well as steady-state infiltration, and to consistently capture treatment effects, our analysis only included values of steady-state infiltration (i.e., the final infiltration or constant rate, regardless of initial soil moisture conditions (Hillel 1998). We included studies that reported different measures of steady-state infiltration (e.g., the total volume of water infiltrated over a defined period). When experiments included multiple measurements of infiltration rate in an individual crop season or year, measurements were averaged. When experiments reported measurements over several years, each value was included separately.

Statistical Analysis

The main statistical analysis was conducted by calculating response ratios, representing a comparison of the experimental to control treatments, as is common in meta-analysis methodology (Hedges et al. 1999). Response ratios represented the natural log of the infiltration rate measured in the experimental treatment divided by the infiltration rate measured in the control treatment. A weighting factor was included in the statistical model as suggested by Philibert et al. (2012) and was created based on the experimental replications of each study (Adams et al. 1997) for the crop comparisons only. Due to the limited reporting of standard errors or standard deviations, as well as the fact that many grazing studies do not include true replications (experimental designs frequently included only subsamples from larger areas or transects, as opposed to a true randomized block design), we performed an unweighted meta-analysis for the grazing experiments (Eldridge et al. 2016).There were a few studies that represented experimental designs and that took subsamples from larger areas rather than taking independent samples from true randomized block designs, and for these studies we assigned a replication value of “1,” which would ascribe a lower weight in the statistical calculations for these experiments (five studies fell into this criteria). Natural log results were back-transformed to a percent change to ease interpretation of results. Results were considered significant if the 95 percent confidence intervals did not cross zero.

An additional analysis was conducted to evaluate the absolute change in infiltration rates (as compared to the response ratio) to demonstrate the magnitude of potential improvement in relation to more intense precipitation events. When possible, values for infiltration rates were converted to mm hr-1 to evaluate the absolute difference between experimental treatments and control treatments. For this portion of the analysis, we counted only values where absolute infiltration rates were reported (as compared to a volume of water infiltrated). We considered a threshold of a one inch per hour (25 mm hr-1) to represent a significant rain event.

For the main statistical analyses, the five different practices were analyzed separately, because there were notable differences in experimental designs and in control treatments. We looked at the full dataset for more observational comparisons including the overall trends and the absolute change in infiltration rates. A mixed model (lme4 package in R) was used to calculate category means and standard errors, including a random effect of study to account for similar study environments when experimental designs allowed for multiple paired observations (e.g., different tillage practices, different cover crop species) (St. Pierre 2001). Groups were considered to be statistically significant if error bars did not cross zero.

TABLE A.1. Description of Experiments included in the Meta-Analysis Database: Cropping System Comparisons

State/Region, Country	Category	Main Cropping System and Description of Experimental Treatment	Control Treatment	Reference
Denmark	cover crop, no-till	barley with radish cover crop, no-till	no cover crop, conventional tillage, reduced tillage	Abdollahi and Munkholm 2014
Texas, USA	crop rotation, no-till	sorghum-wheat	continuous sorghum, reduced tillage	Alemu, Unger and Jones 1997
Yurimaguas, Peru	crop and livestock	trees, pasture, maize, and livestock grazing	trees and pasture^	Arevalo et al. 1998
British Columbia, Canada	no-till	continuous barley	conventional tillage	Arshad, Franzluebbers and Azooz 1999
Central Mexico	cover crop, no-till	no-till, maize with vetch or oat cover crop	conventional tillage, maize without a cover crop	Astier et al. 2006
Uttarakhand, India	no-till	rice-wheat no-till	conventional tillage	Bajpai and Tripathi 2000
Santa Cruz, Bolivia	no-till	wheat-soybean-sunflower no-till	conventional tillage, reduced tillage	Barber et al. 1996
Texas, USA	no-till	wheat-sorghum-fallow no-till	reduced tillage	Baumhardt and Jones 2002
Texas, USA	crop rotation	wheat-sorghum	continuous wheat	Baumhardt, Johnson and Schwartz 2012
Uttar Pradesh, India	no-till	rice-wheat no-till	conventional tillage, reduced tillage	Bazaya et al. 2009
NSW, Australia	crop and livestock	wheat or canola with sheep grazing	canola and wheat only	Bell et al. 2011
Iowa, USA	perennial	silver maple, grass filter, switchgrass, grazed pasture#	maize-soybean*	Bharati et al. 2002
Uttarakhand, India	no-till	rice-wheat no-till	conventional tillage	Bhattacharyya et al 2008
Kansas, USA	crop rotation	sorghum-wheat-soybean	continuous sorghum	Blanco Canqui et al. 2010
Kansas, USA	cover crop	winter wheat-grain sorghum with sunnhemp and late maturing soybean cover crops	winter wheat-grain sorghum with no cover	Blanco Canqui et al. 2011
Georgia, USA	no-till	sorghum-soybean no-till	conventional tillage, reduced tillage	Bruce et al. 1990

Georgia, USA	cover crop and no-till	soybean-grain sorghum-crimson clover no-till~	conventional tillage soybean-grain sorghum-fallow	Bruce et al. 1992
Southern Malawi	perennial	maize with sesbania, gliricidia, leucaena, acacia intercrops	continuous maize	Chirwa, Mafongoya and Chintu 2003
Oklahoma, USA	no-till	continuous wheat no-till	conventional tillage	Dao 1993
Northern Pampean Region, Argentina	crop and livestock	maize-soybean and grass alfalfa pasture rotation with cattle grazing	maize-soybean only	Fernandez, Alvarez and Taboada 2015
Kampala, Uganda	cover crop	maize-bean with crotaleria green manure	maize-bean only	Fischler, Wortmann and Feil 1999
California, USA	cover crop	almond orchard with bromegrass or clover cover crop, tomato with oat or vetch cover crop	orchard no cover crop, tomato no cover crop	Folorunso et al. 1992
Ibadan, Nigeria	no-till	continuous maize no-till	reduced tillage	Franzen et al. 1994
Georgia, USA	crop and livestock	varied intensity cattle grazing on forage grass	hayed forage grass^	Franzluebbers et al. 2012
Georgia, USA	no-till	sorghum-maize-cereal rye cover crop no-till, winter wheat-pearl millett cover crop no-till	conventional tillage	Franzluebbers et al. 2008
Meerut, India	no-till	rice-wheat no-till	conventional tillage, reduced tillage	Gangwar et al. 2006
Central Indus Plain, India	cover crop	rice-wheat-sesbania green manure	rice-wheat without cover crop	Ghafoor et al. 2012
Meghalaya, India	perennial	perennial grasses cut for livestock feed	continuous cultivation annual crops	Ghosh et al. 2009
Southern Nigeria	no-till	maize-maize-cowpea no-till	conventional tillage	Ghuman and Lal 1992
Southwest Spain	no-till	oat-triticale-vetch-brassica no-till	conventional tillage	Gomez-Paccard et al. 2015
Central Mexico	crop rotation, no-till	maize-wheat (crop rotation), no-till	continuous maize and continuous wheat (crop rotation)*, conventional tillage	Govaerts et al. 2007
Erzurum, Turkey	no-till	wheat-vetch no till	conventional tillage, reduced tillage	Gozubuyuk et al. 2014
California, USA	cover crop	grape vineyard with bromegrass cover crop	grape vineyard no cover crop	Gulick et al. 1994
Dodoma, Tanzania	no-till	sorghum no till	conventional tillage, reduced tillage	Guzha 2004
Shaanxi Province, China	no-till	winter wheat no-till (with residue retention)~	conventional tillage	He et al. 2009
Uttar Pradesh, India	no-till	rice-wheat no till	conventional tillage	Jat et al. 2009
Uttar Pradesh, India	no-till	maize-wheat no till	conventional tillage	Jat et al. 2013
Punjab Province, Pakistan	cover crop	wheat-cotton with a jantar green manure	no cover crop	Kahlown and Azam 2003
Iowa, USA	cover crop	maize-soybean-winter rye cover crop	maize-soybean no cover crop	Kaspar, Radke and Laflen 2001
Ibadan, Nigeria	no-till	maize-cowpea-soybean no-till	conventional tillage	Kayombo et al. 1991
Southern Ethiopia	perennial	maize, forestry, and cattle grazing#	continuous maize with tillage	Ketema and Yimer 2014
West Bengal, India	no-till	peanut no-till	conventional tillage, reduced tillage	Khan 1984
Ohio, USA	crop rotation, no-till	maize-soybean, no-till	continuous maize, reduced tillage	Kumar et al. 2012
Meghalaya, India	no-till	groundnut-rapeseed no-till	conventional tillage	Kuotsu et al. 2014
South-Limbourg, Netherlands	cover crop	maize silage with winter rye or summer barley cover crops	no cover crop	Kwaad and Van Milligan 1991
Ibadan, Nigeria	cover crop	maize-cowpea-pigeon pea-cassava-soybean with cover crops	no cover crop	Lal et al. 1978
Ibadan, Nigeria	no-till	continuous maize	moldboard plow, ridge till,	Lal 1997

			disc plow	
Ohio, USA	no-till	maize-soybean no-till	reduced tillage	Lal et al. 1989
Rajasthan, India	no-till	sorghum interseeded with green gram	conventional tillage, reduced tillage	Laddha and Totawat 1997
Georgia, USA	perennial	long leaf pine, planted pine	corn-soybean conventional tillage	Levi et al. 2010
North Dakota, USA	perennial, no-till	grazed pasture (perennial), spring wheat-winter wheat no-till (no-till)~	annual cropping sequence with no grazing (perennial), conventional tillage with spring wheat-fallow (no-till)	Liebig et al. 2004
North Dakota, USA	crop and livestock, perennial	oat/pea-triticale/sweet clover-maize no till with grazing animals (crop and livestock), western wheatgrass pasture cut for forage (perennial)	hayed pastured grass (crop and livestock)*^, oat/pea-triticale/sweet clover-maize no till with grazing animals (perennial)	Liebig et al. 2011
Pulawy, Poland	no-till	maize-spring barley-winter rape-winter wheat-faba bean no-till	conventional tillage, reduced tillage	Lipiec 2006
Mississippi, USA	no-till, cover crop	cotton-soybean no-till with rye or vetch cover crop	no cover crop, reduced tillage	Locke et al. 2012
Iowa, USA	no-till	maize-soybean no-till	conventional tillage, reduced tillage	Logsdon et al. 1992
Punjab Province, Pakistan	cover crop	cotton-wheat with berseem grown as a green manure	cotton-wheat no cover crop	Mahmood-ul-Hassan, Rafique and Rashid 2013
Tel Hadya, Syria	crop and livestock	wheat-lentil-chickpea-vetch-watermelon with livestock	crops only no grazing	Masri and Ryan 2006
Georgia, USA	cover crop	grain sorghum with vetch or wheat cover crop	sorghum fallow no cover crop	McVay et al. 1989
New York, USA	no-till	maize no-till	plow tillage	Moebuis Clune 2008
Parana, Brazil	no-till	wheat-soybean no-till	conventional tillage	Moraes et al. 2016
Uttar Pradesh, India	no-till	rice no-till	conventional tillage	Naresh et al. 2014
Kpong, Ghana	cover crop	maize with stylosanthes guianesis, mucuna pruriens, and mimosa invisa cover crops	maize no cover crop	Nyalemegbe et al. 2011
Harare, Zimbabwe	crop rotation, no-till	maize-sesbania and maize-A. angustissima (crop rotation), no-till	continuous maize (crop rotation), conventional tillage	Nyamadzawo et al. 2003, Nyamadzawo et al. 2008
Seville Province, Spain	no-till	wheat-sunflower no-till	conventional tillage, reduced tillage	Pelegrin et al. 1990
Multiple North America locations: South Dakota, North Dakota, Nebraska, Saskatchewan	crop rotation, no-till	maize-soybean-spring wheat-alfalfa (crop rotation), maize-soybean-sorghum-oat/clover (crop rotation), spring wheat-lentil (crop rotation), spring wheat-pea no-till	continuous maize (crop rotation x2 locations), spring wheat only (crop rotation), spring wheat-pea conventional tillage	Pikul et al. 2005
Western Australia	crop and livestock	pasture grazed with sheep	hayed pasture^	Proffitt et. al 1995
Punjab Province, India	no-till	soybean-wheat no-till	conventional tillage	Ram et al. 2013
Central Mozambique	crop rotation	maize-pigeonpea intercrop	continuous maize	Rusinamhodzi et al. 2012
Entre Rios Province, Argentina	no-till	wheat-maize-soybean no-till	reduced tillage	Sasal et al. 2006
Uttarakhand, India	no-till	rice-wheat no-till	conventional tillage, reduced tillage*	Sharma et al. 2005
Uttarakhand, India	cover crop	maize-wheat with sunnhemp, leucaena green manures	maize-wheat no cover crop	Sharma et al. 2010
Jammu and Kashmir, India	no-till	maize-wheat no-till	conventional tillage, reduced tillage	Sharma et al. 2011
Alaska, USA	no-till	barley no-till	conventional tillage, reduced tillage	Sharratt et al. 2006
Edmonton, Canada	no-till	continuous barley no-till	conventional tillage	Singh et al. 1996
Punjab Province, India	cover crop	rice-wheat with sesbania aculeata green manure	rice-wheat without cover crop	Singh et al. 2007
Uttar Pradesh, India	no-till	rice-maize no-till	conventional tillage	Singh et al. 2016

NSW, Australia	no-till	barley-oats no-till	conventional tillage	So et al. 2009
Hawkes Bay, New Zealand	no-till, cover crop	summer-winter vegetables (tomato, broad bean, sweet maize, cauliflower, sweet pepper, broccoli) with annual ryegrass cover crop (cover crop), no-till summer-winter vegetables	conventional tillage, no cover crop	Springett et al. 1992
Maryland, USA	cover crop	maize with rye cover crop	no cover crop	Steele et al. 2012
Nkhotakota and Dowa districts, Malawi	crop rotation, no-till	maize-cassava-pigeon pea (crop rotation), no-till	continuous maize (crop rotation), conventional tillage	TerAvest et al. 2015
Central Greece	cover crop	cotton with vicia sativa or durum wheat cover crop	no cover crop	Terzoudi et al. 2007
Monze, Zambia	crop rotation	maize-cotton, maize-sunnhemp	continuous maize	Theifelder and Wall 2010
Australia	no-till	sorghum-wheat no-till	conventional tillage, reduced tillage	Thorburn et al. 1992
Queensland, Australia	crop rotation	lucerne, medic annual pasture and wheat#	continuous wheat	Thomas et al. 2009
Uttarakhand, India	no-till	rice-wheat	conventional tillage	Tripathi et al. 2007
Punjab Province, India	cover crop	rice-wheat-Sesbania green manure	no cover crop	Walia et al. 2010
Shaanxi Province, China	perennial	alley cropping with walnut-wheat, monoculture walnut	continuous wheat	Wang et al. 2015
Ibadan, Nigeria	cover crop	maize-cowpea-cassava with cover crops	no cover crop	Wilson and Lal 1982
Haryana, India	no-till	rice-wheat no-till	conventional tillage	Yaduvanshi and Sharma 2014

* Averaged controls

Experimental treatment confounded by livestock

~ He et al. et al. (2009) was confounded by the presence of residue retention in the experimental treatment; Liebig et al. (2004) was confounded by a second crop of winter wheat in the experimental treatment; and Bruce et al. (1992) was confounded by a different tillage system in the control (no-till plus a cover crop versus conventional tillage, no cover crop).

TABLE A.2. Description of Experiments Included in the Meta-Analysis Database: Changes in Grazing Management Complexity

*	First Author	Year Pub.	Site	Prec (mm)	Live-stock	Vege-tation	Dur (Y)	Trt	SR	(Orig) AU/ha	d/y	ha/AU/y	(Trt) AU/ha	d/y	ha/AU/y	rest (d)	% red. SR	Notes
	Sharrow	2007	US, OR	1085	S	Pasture (clover, perennial ryegrass, annual grasses)	11	For	? (M)	60.00	8	1	-	-	-	-	-	300-400 ewes/ha; Apr, Jun; 4:60; res:5 cm
E	Dedjir Gamougoun	1984	US, NM	384	L	Prairie (shortgrass prairie, grasses, forbs)	12	R	H	0.08	270	17	0.18	120	17.3	91	0	Rot (4-3)
	Kumar	2012	US, MO	967	C (beef, 520 kg)	Pasture (tall fescue, red clover)	3	R	M	-	210	-	-	35	-	17.5	0	Rot (6-paddock, 3 cattle)
E	McGinty	1978	US, TX	572	M (C,S,G; 3:1:1)	Woody (mesquite, threeawn, sideoats)	7	R	H	0.23	315	5	0.26	274	5.2	91	4	DR (4-3)
E	Pluhar	1987	US, TX	680	C (cow-calf)	Prairie (midgrass, shortgrass, native)	24	R	M	0.20	315	5.8	0.30	274	5.8	91	0	DR (4-3)
	Proffitt	1995	Australia	307	S	Pasture (annual legume pasture-wheat)	1	Ada	? (M)	1.40	119	2.2	1.40	81	3.2	3	48	Removed occasionally based on soil moisture
E	Tadesse	2002	Ethiopi	1360	M (C,S,G)	Perennial	4	R	H	21.95	36	0.02	65.97	15	0.01	4	603	3d/wk

			a			(native grasses, forbs)					5			6				
	Teague	2010	US, TX	648	C (beef)	Woody (mesquite savanna, grass & forbs)	3	R	M	0.12	220	14	0.95	28	14.0	68	0	Rot (8-1); based on res
E	Teague	2011	US, TX	820	C (cow-calf)	Prairie (tall grass)	9	R	H	0.45	220	3.7	12.32	8	3.7	55	0	PMR (based on res)
E	Thurow	1986	US, TX	609	M (C,S,G)	Woody (oak mottes, bunchgrass, sodgrass)	4	R	H	0.33	240	4.6	4.46	18	4.6	50	0	SD (14-1; 4:50d)
E	Weltz	1986	US, NM	426	C	Woody (blue grama, grasses, forbs)	2	R	H	0.07	365	13.5	-	-	14.0	50	4	SD (4d graze)
E	"	"	"	"	"	"	3	R	M	0.04	365	26.6	-	-	13.3	50	-50	SD (3d graze)
E	Wood	1981	US, TX	680	C (cow-calf)	Woody (wintergrass, sideoats grama)	4	R	M	0.29	200	6.2	3.30	17	6.5	119	5	HILF; 8-1; 17:119
E	"	"	"	"	"	"	20	R	M	0.29	200	6.2	0.16	365	6.2	120	0	DR (4-3, 12:4m)

Note: Studies that also had an exclosure treatment are indicated with an *E* in the leftmost column. Abbreviations used in this and following tables include: Livestock: C (cattle), M (mixed), S (sheep), G (goats), L (livestock); Dur (Y) = treatment duration in years; Trt = Grazing system treatment: C (continuous grazing), R (rotational grazing), Ada (adaptive grazing), For (agroforestry system); SR =stocking rate category: L (light), M(medium), H(heavy), if unclear, a "?" was added; "d/y" = number of days of grazing any given unit of land per year; rest (d) = number of days of rest of any given unit of land/year; % red. SR = the percent that stocking rates (ha/AU/y) were reduced as estimated by available data. While most studies noted that only complexity and not stocking rates were changed, there were a few exceptions. In the notes, specific grazing systems were noted if mentioned clearly by the authors: HILF: High intensity low frequency, DR: Deferred rotation, SD: Short duration, PMR: Planned multipaddock rotational, Rot: Rotational, Res: Residual biomass.

TABLE A.3. Description of Experiments Included in the Meta-Analysis Database: Changes in Grazing Rates or Pressure

	First Author	Year	Site	Prec (mm)	Live-stock	Vegetation	Dur (Y)	Sys	SR (Orig)	SR (Trt)	(Orig) AU/ha	d/y	ha/AU/y	Variable changed	V0	V1	V2	V3	**Notes**
E	Bari	1993	Pakistan	625	L	Grass (grasses, forbs)	2	C	H	M,L	-	-	-	Res phytomass (kg/ha)	624	65	131	-	300-400 ewes/ha; Apr, Jun; 4:60; res:5 cm
	Chartier	2011	Argentina	258	S	Woody (grass to shrub steppe; perennial grasses)	-	C	H	M,L	0.1	365	16.7	Veg	Grass steppe	Grass steppe	Shrub steppe	-	Rot (4-3)
E	Dedjir Gamougoun	1984	US, NM	384	L	Prairie (shortgrass prairie, grasses, forbs)	3	C	H	M	-	-	17.3	ha/AU	17	25	-	-	Rot (6-paddock, 3 cattle)
E	du Toit	2009	S Africa	366	S	Woody (common shrubs, karoo bushes, grasses)	2	C	H	M,L	1.8	30	6.8	SSU/ha	16	50	75	-	DR (4-3)
E	Franzluebbers	2011	US, GA	1250	C (yearl. steers)	Pasture (Bermuda grass, tall fescue; hayed 1/mo to 5cm	12	C	H	L	4.1	270	0.3	steer/ha	9	33	-	-	DR (4-3)
E	Mwendera	1997	Ethiopia	1000	C (cows, oxen)	Perennial (native grasses)	1	C	V	L,M, H	-	365	0.8	AUM/ha	4	29	57	86	Removed occasionally based on soil moisture

E	Pluhar	1987	US, TX	680	C (cow-calf)	Prairie (midgrass, shortgrass, native range)	1	R	V	H	12.5	8	3.6	ha/cow/y	13	66	-	-	3d/wk
E	Savodogo	2007	Burkina Faso	841	M (C, S, G, wild)	Woody (savanna, annual/perennial grass)	1	R	V	L,M, H	0.2	40	45.6	280kg/d/ha	8	25	50	75	Rot (8-1); based on res
E	Taddese (b)	2002	Ethiopia	1000	C (cow, oxen)	Perennial (native grasses)	1	C	V	L,M, H	-	365	3.4	AUM/ha	4	29	57	86	PMR (based on res)
E	Tadesse	2003	Ethiopia	1095	C (cow)	Perennial (native grasses, forbs)	2	C	H	M	-	365	3.4	AUM/ha	4	57	-	-	SD (14-1; 4:50d)
E	Teague	2011	US, TX	820	C (cow-calf)	Prairie (tall grass prairie)	9	C	H	L	0.4	220	3.7	AU/100ha	27	48	-	-	SD (4d graze)
E	Thurow	1986	US, TX	609	M (C, G, S)	Woody (oak mottes, bunchgrass, sodgrass)	6	C	H	M	0.3	240	4.6	ha/au/y	5	43	-	-	SD (3d graze)
	Warren (a)	1986	US, TX	609	M (C,G,S; 1.63:1:1)	Woody (live oak, grass, savanna)	2	R	H	M,L	2.9	26	4.8	ha/AU	0.3	37	53	-	HILF; 8-1; 17:119
E	Warren (b)	1986	US, TX	609	C (heifers)	Bare (herbicide + drought killed forbs)	1	R	V	M,H	6.8	20	2.7	ha/AU/y	2.7	34	67	-	DR (4-3, 12:4m)
E	Weltz	1986	US, NM	426	C	Woody (blue grama, grasses, forbs, etc.)	18	C	H	M	0.1	365	13.5	ha/AU	14	25	-	-	
E	Wood	1981	US, TX	680	C(cow-calf)	Woody (winter grass, sideoats grama, mesquite)	20	C	H	M	0.2	365	4.6	ha/AU	5	25	-		
E	Zhou	2010	China	505	M (G,S, 4:1)	Grass	13	C	H	M	0.2	365	-	trampling	H	M	-	-	trampled path vs. pasture

Note: The "variable changed" as reported by the authors is listed in the table, and the original value (V0) of that variable is noted as well as the percent reduction (V1, V2, V2, represent the value that the given variable decreased by as calculated from reported data and in order of increasing degree of change.) Abbreviations are as noted above.

TABLE A.4. Description of Experiments Included in the Meta-Analysis Database: Exclosure Experiments (not included in A.3. or A.4.)

First Author	Year	Site	Prec (mm)	Livestock	Vegetation	Dur (Y)	Sys	SR (Orig)	AU/ha	d/y	ha/AU/y	**Grazing Notes**	**Excl. Notes**
Achouri	1984	US, UT	250	C	Perennial (crested wheatgrass)	20	C	M	-	90	4.5	M (1.5 ha/AUM) for several y (Jun-Aug)	ungrazed for >20 y
Allington	2011	US, AZ	395	C	Perennial (hairy grama, grasses, shrubs)	40	R	M (?)	0.1	7	-	SDRG (<1wk); avg of 1AU/13ha	Research ranch (ungrazed), across fence
Bharati	2002	US, IA	851	C	Pasture (grass, brome, timothy)	6	C	-	-	-	-	"C grazed pasture"	"Grass filter" (ungrazed area)
Busby	1981	US, UT	345	C	Perennial (crested wheatgrass, deforested pinyon-juniper)	5,1	R?	M	-	75	-	"M to H" May1-Jun15 & Oct1-Nov1; 3 trt	Ex in each trt
Castellano	2007	US, AZ	350	L	Shrub/Desert (acacia, etc.)	52, 25, 10	C	-	-	-	-	Open grz since late 1800s	3 ex: 1997(20ha), 1993 (1ha), 1958 (9.3ha)
Gifford	1982	US, ID	305	C	Perennial (crested wheatgrass, grass; rep big sagebrush)	1,2,4,6	C	-	-	120	-	Seasonal	3 30x30m ex installed
Jeddi	2010	Tunisia	196	L	Steppe (arid, degraded)	6,12	C	-	-	-	-	C grazed area	Ex set up gradually by Sfax FS
Kato	2009	Mongolia	181	M(S,G,C,H)	Grass steppe (perennial grass, forbs, tallgrass)	4	C	V	-	365	-	"long been subject to intensive grazing"	1.5m fence
"	"	"	213	"	Grass steppe	4	C	H	-	365	-	"L #'s have increased considerably"	1.5m fence

"	"	"	162	"	Shrub/Desert (acacia, etc.)	4	C	M	-	365	-		Airport grounds; trt likely >4y but not reported
Kauffman	2004	US, OR	320	C	Meadow (dry & wet, herb. riparian plants, grass, sedge)	7	C	M (?)	-	75	-	1 site: deferred grz, summer; 2 sites: July1-Sept15);	Avg of ex at each (19,7,7), accidental and wild grazing has occurred; wet, dry meadows measured separately at each of 3 sites
Krzic	1999	BC	355	C(Cow-Calf)	Pasture (lodgepole pine plantations)	8	C	M (?)	-	30	-	Grz to 50% forage use for 1 summer mo;	2 0.5ha ex (1 for each of 2 seeding trt); protection from new grazing (not grazed previously).
Lavado	1994	Argentina	950	C(Cow-Calf)	Perennial (Natural vegetation, grasses)	3, 12	C	H	1.4	365	0.7	Reported in AU/ha/y; "C grz in a H SR"	2 2-ha enclosures of different ages (3, 12 y)
Takar	1990	Somalia	446	M(C,G)	Grass (shrubs, annual grass/forbs)	3	C	H	-	365	5	"grazed heavily w/C&G by seminomadic pastoralists"	2-ha livestock exclosure
Tukel	1984	Turkey	362	L	Grass (steppe, forage grass, shrubs)	30	C	H	-	365	-	"heavy grazing on public range"	protected area
Tromble	1974	US, AZ	312	M(C,G,S)	Grass (black grama, fmesquite,annuals)	9	-	-	-	-	-	"grazed"	"ungrazed site had been protected from livestock use for the past 9 y"
Wheeler	2002	US, CO	407.7	C (Steers)	Riparian (willows, sedge)	39	C	H	20.4	5	-	1x H grz (6/0.25 ha) on protected paddocks; Grz to 60-75% use; avg spring/summer grz	3 ungrazed paddocks/trt

Note: All exclosure studies that were not represented in either of the first two appendices (i.e., studies that did not include a treatment representing increased grazing land management complexity or a reduction in stocking rates or pressure).

Appendix B: Methods and Experiments included in the Porosity and Field Capacity Meta-Analysis[2]

Database Development

The goal of this analysis was to understand the impact of continuous living cover on soil hydrologic properties in agricultural systems using a meta-analysis approach. Therefore, the first step was to develop a database of studies that could be included in the analysis. The two major criteria for database inclusion were (1) studies compared land managed with continuous plant growth (including cases of actively restored perennial landscapes) versus annual crop systems that did not include continuous plant cover; and (2) studies measured at least one of two indicators of soil hydrology: water retained at field capacity (the maximum level of plant-available soil water, hereafter referred to as field capacity) or total porosity (the maximum volume of water that soil can hold). Several different treatment practices representing continuous living cover were sought for inclusion in the database:

1. <u>Cover crops</u>, where a cover crop was grown in between the harvest of annual cash crops (compared to leaving soil uncovered in the control treatment)
2. <u>Perennial grasses</u>**,** including grazing systems with either native or cultivated grasses, Conservation Research Program (CRP) protected conservation lands, perennial bioenergy, or forage crops
3. <u>Agroforestry systems</u>
4. <u>Managed forestry systems</u>

The *EBSCO Discovery Service*™ was the primary search engine used to compile the database for this analysis. It searches a comprehensive collection of titles, including more than 23,000 publications from databases such as JSTOR and publishers such as Wiley, Elsevier, Springer-Nature, IOP, Royal Society, Oxford, Cambridge, Thomson Reuters, AAAS, and the American Society of Agronomy. The *EBSCO Discovery Service*™ matches on subject headings, keywords, and abstracts, making it an ideal search engine for building a database targeted to the highly specific question in this analysis. The keyword search included descriptors of the soil properties (given the multiple terms that might be used to describe field capacity) as well as the different continuous living cover practices. The search terms included were: water retention OR field capacity OR moisture retention OR porosity AND perennial W1 grass* OR cover crop* OR agroforest* OR forest*. These keyword terms found > 400 studies, of which 25 ultimately fit our criteria.

To supplement the *EBSCO Discovery Service*™ search, the USDA-NRCS Soil Health Literature Database (NRCS, 2016) was used to find additional research papers. This database is an ongoing effort of the NRCS Soil Health Division to categorize the impact of conservation practices on soil properties and uses large search databases (including Google Scholar) to find papers. It is updated regularly by staff and currently includes more than 300 peer-reviewed references. The database allows users to search specific soil properties, including water retention and soil porosity, as well as specific treatments based on established NRCS practice codes. From this search, we added two additional studies, for a total of 27 studies representing 93 separate paired observations for both soil properties analyzed. Only three studies included field measurements of both variables.

Several studies had complex treatment or control scenarios and were entered into the database only after careful consideration. Some experimental designs (i.e., with a variety of cover crop or perennial grass treatments) allowed for multiple comparisons to be created within individual experiments. If an experiment included multiple treatments that could be considered a control (i.e., different annual cropping systems, see Tables 1 and 2), these were averaged to represent one control treatment. Also, for some of the most complex studies, it was not possible to develop comparisons between treatments that solely tested the isolated effect of the continuous living cover treatment to an annual cropping system control. For example, several experiments included perennial grasses with livestock grazing compared to annual crops, such that the inclusion of grazing animals was a confounding factor. While not ideal, these studies were maintained in the database as they still represented important differences between annual and perennial based systems.

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[2] Adapted from Basche and DeLonge (n.d.)

Steps were taken to ensure that field measurements were extracted from each paper as consistently as possible. For example, for the field capacity measurements, if authors described a specific potential pressure typical for their location, then this was the potential pressure that was utilized for the database. When experiments did not assign a specific potential pressure associated with field capacity, potentials in the range of -10 kPa to -33 kPa were selected, and if multiple measurements in this range were reported, they were averaged (Hillel 1998; see Table 2). This analysis specifically focused on the wetter range of the water retention curve because the pore sizes that affect this range are the ones understood to be affected by management (Kay 1998). For porosity**,** only studies that included measurements for total porosity, as opposed to measurements of only macro-, micro-, or porosities associated with different particle and aggregate sizes, were included in the database. This was done in an attempt to keep the comparison as standardized as possible across the range of soil textures. If experiments measured properties more than once in a season or for multiple depths, these measurements were averaged to create one comparison per treatment. Several studies reported measurements that were taken at the end of a season for multiple years and these were counted as separate paired observations.

Statistical Analysis

Response ratios were calculated as the ratio of the soil water property measured in areas with continuous living cover treatments as compared in annual cropping system controls. The natural log of the response ratio was calculated for the two soil properties separately and used as the basis for all statistical analyses (Equation 1) (Hedges et al. 1999). For meta-analysis, a weighting factor is typically developed to give more weight to studies with greater levels of precision or lower within-study variability (Philibert 2012). As many of the experiments in this database did not provide measurements of within-study variability (standard deviations or standard errors), the number of experimental replications were used as an alternative method to develop a weighting factor (Equation 2) (Adams et al. 1997). In studies with experimental designs that did not include true replication (i.e., relying instead on multiple subsamples from different treatments), a replication size of “1” was assigned to create a lesser weight for those experiments in the calculation of mean effect sizes (Tables 1 and 2).

The primary statistical analysis was conducted using R (Version 1.0.136, R Core Team, 2009-2016). A mixed effects model (lmer4 package) was used to calculate mean effects, including a random effect of study and the weighting factor of experimental replications. The random effect of study is similar to a “block” effect, accounting for similarities in environments when more than one response ratio was available for one study (Eldridge et al. 2016; St-Pierre 2001). In addition to calculating overall mean effects of treatments for each soil water property, studies were analyzed in groups according to soil texture, annual precipitation, or the inclusion versus exclusion of livestock; for the statistical analysis, these groups were treated as fixed effects. If 95 percent confidence interval did not cross zero, results were considered significant. For ease of interpretation, the log response ratios were back transformed and converted to percentages (Equation 3).

$$LRR = \ln\left(\frac{\text{Experimental Treatment X}}{\text{Control Treatment X}}\right) \quad (1)$$

Where X is either porosity or field capacity

$$Wi = \frac{\text{Experimental Reps * Control Reps}}{\text{Experimental Reps + Control Reps}} \quad (2)$$

$$\text{Percent change} = [\text{Exp(LRR) - 1}] * 100 \quad (3)$$

TABLE B.1. Experiments Measuring Total Porosity in the Meta-Analysis Database

Location	Treatment Category	Control	Treatment	Experimental Design	Reference
Denmark	Cover crop	Spring barley	With radish cover crop	Split plot, 3 replications	Abdollahi and Munkholm al. 2014
Nigeria	Perennial grass	Cereal-legume continuous cropping	Perennial pasture grasses with 2 months controlled grazing	5 adjacent ~2.5 ha field sites, sampled 9 locations from each site	Abu 2013
France	Cover crop	Barley, pea, and wheat without cover crops	With legume cover crops, managed as living mulches	Sampled from 6 locations in each treatment	Carof et al. 2007
Italy	Perennial grass	Continuous wheat	Perennial pasture	2 replications	Chisci et al. 2001
Brazil	Cover crop	Fallow, ruzigrass, sorghum	With sorghum-sudangrass, sunhemmp, millet cover crops	Randomized complete block, 4 replications	Garcia et al. 2013
Iran	Perennial grass	Continuous wheat	Pasture with livestock	Sampled from 6 points in each land use	Haghighi, Gorji and Shorafa 2010
Ethiopia	Agroforestry	Maize-based conventional tillage	Agroforestry based conservation with livestock	Sampled from 4 areas in two adjacent fields	Ketema and Yimer 2014
China	Perennial grass	Annual oats	Perennial pasture with livestock grazing	3 replications	Li et al. 2007
Pakistan	Cover crop	Cotton-wheat	Berseem green manure	4 replications	Mahmood-ul-Hassan, Rafique and Rashid 2013
Victoria, Australia	Perennial grass, agroforestry	Continuous annual cropping	Perennial pasture & alley cropping	2 replications of pasture, 3 replications of alley cropping and continuous annual cropping	Mele et al. 2003
Ontario, Canada	Cover crop	Continuous corn	Corn, corn, oats, barley with red clover cover crop	Randomized split plot, 4 replications	Munkholm, Heck and Deen 2013
Ghana	Cover crop	Maize-fallow	With mucuna, stylosanthes and mimosa cover crops	Split plot, 4 replications	Nyalemegbe et al. 2011
North Carolina	Perennial grass, forestry	Conventionally tilled corn, peanuts, cotton, soybeans	Integrated livestock and pasture, black walnut plantation forestry woodlot	3 replicated blocks (8-ha each) with five subplots for different treatments	Raczkowski et al. 2012
Argentina	Perennial grass	Average of corn and soybean treatments	Pasture	Sampled from 5 locations in each treatment	Sasal et al. 2010
Brazil	Agroforestry	Corn-soybean	Silvopasture, agro-silvopasture with livestock	Adjacent fields, sampled from four transects per field	Silva et al. 2011
Illinois, USA	Cover crop	Corn-soybean	With rye, vetch, rye + vetch cover crop	Randomized complete block, 4 replications	Villamil et al. 2006

TABLE B.2. Experiments Measuring the Water Retained at Field Capacity in the Meta-Analysis Database

Location	Treatment Category	Control	Treatment	Experimental Design	Pressure Reported for Volumetric Water Content Used in LRR	Reference
Nigeria	Perennial grass	Cereal-legume continuous cropping	Perennial pasture grasses with two months controlled grazing	5 adjacent ~2.5 ha field sites, sampled nine locations from each site	Assigned -10 kPa as field capacity	Abu 2013
Iowa, USA	Cover crop	Corn-soybean	With rye cover crop	Randomized complete block, 4 replications	Assigned -33 kPa as field capacity	Basche et al. 2016
Missouri, USA	Perennial grass	Corn-soybean (average of till and no till treatments)	Timothy grass and restored prairie	Sampled from 6 replications in adjacent fields	Reported -10 kPa, -20 kPa, -33 kPa, averaged values	Chandosoma et al. 2016
Missouri, USA	Cover crop, perennial grass	Mulch-till corn-soybean	No-till corn-soybean-wheat with red clover, CRP, pasture	Randomized complete block, 3 replications	Reported -10 kPa, -20 kPa, -33 kPa, averaged values	Jiang et al. 2007
Tennessee, USA	Cover crop	Cotton	With rye-vetch cover crop	4 replications	Reported -10 kPa, -15 kPa, -20 kPa, -30 kPa, averaged values	Kiesling et al.1994
Georgia, USA	Forestry	Corn-soybean conventional tillage	Long leaf pine, planted pine	Randomized complete block, 3 replications	Assigned -10 kPa as field capacity	Levi et al. 2010
Zimbabwe	Agroforestry	Continuous maize	Improved fallow w/ acacia & sesbania	Randomized complete block, 3 replications	Reported volumetric water content between -5 kPa & -33 kPa	Nyamdzawo et al. 2012
Louisiana, USA	Cover crop	Cotton	With common vetch or hairy vetch cover crops	3 replications	Assigned 1/3 atm as field capacity	Patrick et al. 1957
North Carolina	Perennial grass, forestry	Corn, peanuts, cotton, soybeans (average of till and no till treatments)	Integrated livestock and pasture, black walnut plantation forestry woodlot	3 replicated blocks (8-ha each) with five sub-plots for different treatments	Assigned -10 kPa as field capacity	Raczkowski et al. 2012
Texas, USA	Perennial grass, cover crop	Sorghum-wheat conventional tillage	CRP, grazed grassland	Sampled 3 different locations according to soil type in adjacent fields	Reported -10 kPa, -30 kPa, averaged values	Schwarz et al. 2003
Brazil	Agroforestry	Corn-soybean	Silvopasture, agro-silvopasture with livestock	Adjacent fields, sampled from four transects per	Assigned 0.01 MPa as field capacity	Silva et al. 2011

				field		
India	Cover crop	Rice-wheat	With sesbania green manure	Randomized complete block, 3 replications	Assigned 0.3 bars as field capacity	Walia et al. 2010
Nigeria	Cover crop	Maize-cassava-cowpea	With cover crops	Randomized complete block, 3 replications	Assigned pF 2.5 as field capacity	Wilson and Lal 1982
China	Forestry	Wheat, rapeseed, canola	Afforestation	5 samples taken from adjacent fields	Assigned pF 2.5 as field capacity	Yu et al. 2015
Location	Treatment Category	Control	Treatment	Experimental Design	Pressure Reported for Volumetric Water Content Used in LRR	Reference
Nigeria	Perennial grass	Cereal-legume continuous cropping	Perennial pasture grasses with two months controlled grazing	5 adjacent ~2.5 ha field sites, sampled nine locations from each site	Assigned -10 kPa as field capacity	Abu 2013

Appendix C: Methods for the Hydrology Modeling Analysis[3]

Methods

The Basin Characterization Model (BCM) is a grid-based hydrology platform that calculates water balance and has been utilized extensively across the western United States to evaluate hydrologic response to changes in climate (Thorne et al. 2015; Flint et al. 2013; Flint and Flint 2008). Prior applications of the BCM have evaluated how soil improvements through rangeland management alter the hydrologic balance in California. A goal of this analysis was to similarly analyze how soil improvements through agricultural management lead to landscape hydrologic impacts; because the soil profile properties in the BCM represent the central reservoir for water storage and runoff, it was a well-suited tool for this analysis.

We ran the BCM at a monthly time step with a 250-m grid cell size applied to 17 watersheds in Iowa (Figure 1; Table 1). These watersheds were selected to represent the various ecological and climatological regions covering a large geographic extent of the state and to capture watersheds that include or flow into major urban areas. Datasets were developed to reflect the climate (precipitation, temperature, and potential evapotranspiration), soils, geology, land cover, and elevation of Iowa (Table 2). Potential evapotranspiration input data was generated first for clear sky conditions with a solar radiation model that used the Priestley-Taylor equation and incorporated state specific parameters of slope, aspect, and topography. Cloudiness corrections were made using data for 16 stations from the Iowa Environmental Mesonet (IEM 2016; Flint et al. 2013). Soil texture and organic matter data from the Soil Survey Geographic Database (SSURGO; Soil Survey Staff 2016) were used to calculate soil hydraulic properties using the pedotransfer functions outlined in Saxton and Rawls (2006) (Table 2). Values for the permanent wilting point and field capacity were selected based on agricultural soil convention, which is known to vary between locations (1.5 MPa and 0.033 MPa were chosen, respectively; see Hillel 1998). For this BCM application, adjustments were made to explicitly incorporate crop water use. This required a closer estimation of the plant rooting zone, which was then limited in regions of maize and soybean assuming an average rooting depth of 0.8-1m. These crops represent 94 percent of harvested cropland in the state (USDA-NASS 2014).

An iterative calibration was conducted using two main sources of data: (1) a unique dataset created by the United States Geological Survey (USGS) of 1-km^2 evapotranspiration data for the contiguous United States calibrated to several remote sensing products and constrained by water balance calculations (Reitz et al. 2015); and (2) USGS stream flow data for each of the 17 watersheds. Information from additional station locations was sought for watersheds that required addition or subtraction of water flow into station locations. Initial crop and land use k-factors were selected in accordance with the Food and Agriculture Organization (FAO) crop water use guidelines (FAO 1992) and then iteratively adjusted to better reflect stream flow as well as monthly evapotranspiration estimates (Table 3), where actual evapotranspiration was divided by potential evapotranspiration and spatially extracted for individual vegetation types. Bedrock permeability values were also altered to best match stream flow as a proxy for the predominantly tile drained landscape of this region.

Recharge and runoff predicted by the BCM was used with postprocessing equations (see below) to calculate basin discharge for 17 basins and matched to measured hydrographs as described by Flint et al. (2013). Goodness-of-fit statistics included percent bias (PBIAS) values for the 17 basins, ranging from -4.8 to 0.4 percent, and Nash-Sutcliffe Efficiency (NSE) values ranging from 0.16 to 0.78, with an average of 0.55. Moriasi et al. (2007) propose that PBIAS values that are ±25 percent, and all of the basins fell within this range. Further, NSE values > 0.50 are thought to represent satisfactory performance of monthly stream flow predictions (Moriasi et al. 2007). Given that the predominant land use in Iowa is agricultural, and the landscape includes extensive tile drainage, we considered these values to be suitable for our analysis after careful consideration of hydrographs that matched periods of peak flow well.

A series of additional model scenarios were established that evaluated agricultural land use change, subsequent soil improvements, and hydrologic change for historical and future projections of climate (Table 2; Table 4). Given prior research that predicted reduced flood frequency and intensity with more perennial vegetation (Schilling et al. 2014), we sought to understand how, in addition to crop water use, soil hydrologic improvements play a role in these impacts. Further, a global meta-analysis recently found that agricultural management that includes "continuous living cover" (i.e., cover crops, perennials crops, and agroforestry) increases total porosity and field capacity by an

[3] Adapted from Basche et al. (n.d.)

average of 8 to 9 percent compared to annual crop systems (Basche and DeLonge n.d.). These are two important soil hydrologic inputs to the BCM and served as the basis for the land use change scenarios outlined in Table 4. Two other modeling analyses for Iowa, which evaluated the vulnerable and less productive landscape regions, were utilized to evaluate in a geographic fashion where perennial landscapes would be most effectively targeted: (1) the Daily Erosion Project (Cruse et al. 2006), which is an ongoing effort by midwestern scientists to predict at a HUC12 scale the extent of soil erosion using the Water Erosion Prediction Project (WEPP) model, to determine the most erodible regions in the state; and (2) a subfield profitability analysis as described by Brandes et al. (2016) and updated for 2012 to 2015, in which soil characteristics, average crop yields, production costs, and commodity prices were integrated at a subfield resolution to determine regions of the state that were more or less profitable on an annual basis.

We evaluated the National Weather Service "flood stage" values for specific locations that corresponded to our modeled domain. Flood stage is defined as "the stage at which overflow of the natural banks of a stream begin to cause damage in the local area from inundation (flooding)" (USGS 2017a). Flood stage values are equated to a stream flow value by USGS that we used to estimate the number of months that experienced water flows above a particular location's flood stage (USGS 2017b). We then calculated how many of those months had lower flow values in our modeled predicted stream flow compared to the baseline land use and the shifts in most erodible lands scenarios.

The procedure for calculating basin discharge values was as follows (see Flint et al. 2013 for a more thorough review of the postprocessing equations): To compare predictions to measured stream flow data, all grid cells within each basin domain are summed based on the individual grid-cell values of monthly predictions for runoff and recharge. Further, the water balance is conceptualized into three connected groundwater reservoirs: (1) the *surface* reservoir, representing runoff and seepage; (2) the *shallow groundwater* reservoir, representing the shallow transient saturated zone that seasonally provides much of the base flow but can be event driven; and (3) *deep groundwater* reservoir representing any regional aquifer processes and can contribute to the shallow groundwater reservoir.

A series of equations in successive time steps (i) partitions water to represent the three reservoirs, based on the BCM predictions of runoff (BCM_{run}) and recharge (BCM_{rch}).

The surface reservoir:

$$[1]\ GW_{surface(i)} = GW_{surface(i-1)} + BCM_{run(i)} - Surfaceflow_{(i-1)}$$

Where $Surfaceflow_i$ is:

$$[2]\ (SurfaceScaler * GW_{surface(i)})^{SurfaceExp}$$

SurfaceScaler and *SurfaceExp* represent coefficients to match peak and recessional flows and are typically ≤ 1.

The shallow groundwater reservoir:

$$[3]\ GW_{shallow(i)} = GW_{shallow(i-1)} + BCM_{rch(i)} - shallowflow_{(i)} - deepflow_{(i)}$$

$Shallowflow_{(i)}$ is:

$$[4]\ (ShallowScaler * GW_{shallow(i-1)})^{ShallowExp}$$

ShallowScaler and ShallowExp represent coefficients to match base flow that are ≤ 1.

The deep groundwater reservoir:

$$[5]\ Deepflow_{(i)} = (DeepScaler * GWshallow_{(i-1)})^{DeepExp}$$

This reservoir is subtracted from the shallow reservoir to simulate deep groundwater recharge. *DeepScaler* and *DeepExp* are coefficients that are ≤ 1 used to maintain a mass balance of water flow by limiting shallow groundwater entering stream flow.

Stream flow upstream of the observation gage is calculated as the sum of the surface and shallow reservoirs.

$$[6]\ Stream_{(i)} = GW_{surface(i)} + GW_{shallow(i)}$$

Basin discharge:

$$[7]\ Discharge_{(i)} = AquiferRch * Stream_{(i)}$$

AquiferRch is a coefficient used to account for impairment to flows where basins gain (>1) or lose flow (<1) in the long term. BCM predictions of runoff and recharge represent hydrologic conditions that are assumed free of additional processes such as diversions, reservoir storage, urban runoff, or groundwater pumping. These assumptions could further account for errors between measured stream flows in the modeled domains. Approximately 30 to 40 percent of harvested cropland in Iowa includes subsurface tile drainage (USDA 2014; Sugg 2007), which can be considered an additional process unaccounted for by explicit model representations. As a result, aquifer recharge values were generally lower than 1 in our post-processing equations (average of 1.03).

TABLE C.1. Stream Gauges and Watersheds Used in BCM Simulations in Iowa, Discharge Equation Coefficients and Goodness of Fit Statistics

Station Name	NWIS Station	SurfaceExp	ShallowScale	ShallowExp	DeepScale	DeepExp	AquiferRch	NSE	PBIAS
Fort Dodge	5480500	0.99	1	0.99	1	0.85	1.06	0.54	-0.81
Cedar Rapids	5464500	0.99	1	0.95	1	0.92	0.96	0.47	-0.28
Omaha	6610000	0.99	1	0.9	1	0.65	0.91	0.51	-0.38
Independence	5421000	0.99	1	0.97	1	0.88	0.96	0.65	0.21
Van Meter	5484500	0.99	1	0.94	1	0.88	1.02	0.59	-0.27
Sigourney	5472500	0.98	1	0.9	1	0.95	1.1	0.59	-4.84
Randolph	6808500	0.98	1	0.85	1	0.97	0.98	0.78	-0.60
Ottumwa	5489500	0.99	1	0.94	1	0.78	1.06	0.16	0.11
Red Oak	6809500	0.99	1	0.94	1	0.95	0.93	0.72	0.29
Clarinda	6817000	0.99	1	0.9	1	0.95	0.79	0.70	-0.70
Rowan	5449500	0.99	1	0.97	1	0.91	1.03	0.48	-0.03
Ames	5471000	0.99	1	0.97	1	0.93	1.02	0.42	-0.20
Marengo	5453100	0.99	1	0.87	1	0.94	1.32	0.50	0.38
Wapello	5465500	0.97	1	0.84	1	0.94	1.09	0.33	-0.02
Garber	5412500	0.99	1	0.88	1	0.88	0.93	0.70	-0.53
Maquoketa	5418500	0.97	1	0.8	1	0.9	0.94	0.61	-0.07
Dewitt	5422000	0.96	1	0.85	1	0.88	1.4	0.54	-0.44

TABLE C.2. Crop Coefficients Used for Various Crop and Land Uses

	Data	Source	Reference
Soil	Soil texture and % organic matter (to generate the upper and lower end of plant available water, and total porosity)	SSURGO	SSURGO, Saxton and Rawls 2006
Climate	Precipitation, temperature (Tmax, Tmin), potential evapotranspiration	PRISM, Iowa Environmental Mesonet	IEM 2016
Climate	Future climate change (RCP 8.5)	CMIP5	CMIP5 2016
DEM	Digital elevation map	USGS	USGS 2015
Geology	Geology	USGS	USGS 2005
Land Use	2016 cropland data layer	USDA	USDA-NASS 2017
Additional Scenarios	Erodible land	Cruse et al. 2006	Subfield Profitability Analysis
	Daily Erosion Project	Regions of greater and lesser profitability	Brandes et al. 2016

FIGURE C.1. Geographic Extent of Modeling and Watershed Boundaries

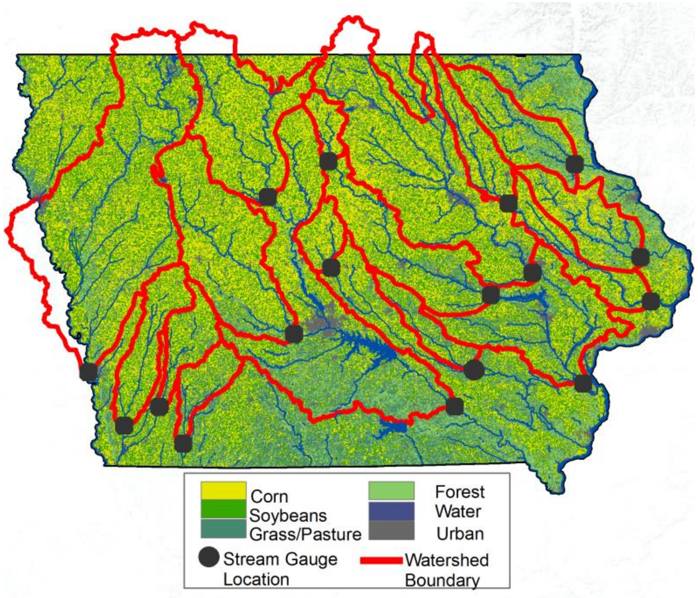

TABLE C.3. Crop Coefficients Used for Various Crop and Land Uses

	Corn	Soybean	Pasture	Alfalfa	Forest	Water	Urban	Wetland
Oct	0.20	0.20	0.13	0.13	0.12	0.18	0.04	0.18
Nov	0.13	0.12	0.11	0.12	0.11	0.19	0.05	0.19
Dec	0.05	0.05	0.12	0.13	0.10	0.12	0.11	0.12
Jan	0.05	0.05	0.09	0.11	0.15	0.05	0.10	0.05
Feb	0.05	0.05	0.09	0.10	0.14	0.06	0.08	0.06
Mar	0.05	0.05	0.11	0.11	0.14	0.08	0.12	0.08
Apr	0.20	0.20	0.11	0.11	0.32	0.15	0.14	0.15
May	0.25	0.25	0.27	0.28	0.32	0.25	0.17	0.25
Jun	0.50	0.50	0.27	0.27	0.36	0.29	0.19	0.29
Jul	1.03	1.03	0.39	0.39	0.42	0.39	0.19	0.39
Aug	1.06	1.06	0.49	0.49	0.48	0.40	0.16	0.40
Sep	0.50	0.50	0.37	0.37	0.39	0.32	0.09	0.32

TABLE C.4. Land Use Change Scenarios Evaluated in the Analysis

Scenario	Changes	Timeframe
Baseline	Current land use and soil conditions	Historic: 1981–2015, Future: 2070–2099^
EROD	Perennial crops* on all cropland with >5 tons $acre^{-1}$ erosion rates, corn or soybean with a cover crop* on cropland with 2–5 tons $acre^{-1}$ erosion rates, land converted has 8–9% improvement in field capacity and porosity	Historic: 1981–2015, Future: 2070–2099^
PROF	Perennial crops on cropland that is the least profitable regions (mean profitability 2012–2015 below $-82 ha^{-1}), corn or soybean with a cover crop on the next least profitable regions ($-82 to $56 ha^{-1}), land converted has 8–9% improvement in field capacity, porosity	Historic: 1981–2015, Future: 2070–2099^

* Kfactors for additional perennial plants were based on the calibrated pasture kfactors (C.3.) and from FAO values for pasture grass (1992). For corn or soy with a cover crop, the summer month (June to September) used the kfactors for corn or soybean, while for the remaining months pasture kfactors were used (minus May when it was lowered slightly to better represent cover crop termination before cash crop planting) (FAO 1992).

^ Future climate included analysis of three different global climate models using the representative carbon pathway 8.5: Canadian Centre for Climate Modeling and Analysis (CanESM2), Japan Agency for Marine-Earth Science and Technology (MIROC-ESM), and the Met Office Hadley Center (HadGEM2-ES). These were selected based on global average temperature and precipitation changes predicting a range of wetter, drier, hotter, and cooler average changes by the end of the 21st century. For the locations selected in this analysis, the three GCMs predicted an average increase in rainfall of 4.9 percent and a maximum temperature increase of 7 to 9ºC for the 2070 to 2099 period.

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