

Using CropSyst to Evaluate Biochar as a Soil Amendment for Crops

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Abstract

A computer simulation study was conducted to evaluate the potential effect of biochar addition to a loamy sand soil with low water holding capacity, with the expectation that two biochars (with high and low ammonium adsorption capacities) added at rates of 96 and 288 tons per hectare to a soil depth of 0.3 m would increase water retention, decrease nitrogen losses, and increase yields of potatoes. The simulations were performed using a cropping system simulation model (CropSyst) that considered full irrigation, deficit irrigation, and no irrigation treatments and covered a period of 30 years using weather data from a location near Moses Lake, Washington. The effect of biochar additions on potato yields was negligible under full irrigation. However, when soil water limited crop growth (deficit and no irrigation treatments), small yield gains of ~4% were projected. This result is consistent with dryland cereal crop experiments reported in the literature, conducted in agricultural soils not limited by low pH or low fertility. The addition of biochar to irrigated crops under full irrigation is unlikely to be advantageous unless acidic conditions are improved by biochar additions. Yields of dryland crops grown in the Inland Pacific Northwest might benefit, particularly when applied at high rates, although the economic benefit of biochar addition at these rates will require evaluation. Regarding nitrogen, the relatively fast conversion of ammonium to nitrate (nitrification) neutralized the effect of the additional ammonium sorption capabilities from the biochars, providing no advantage. It is unclear if biochar can provide a degree of protection against the microbial activity responsible for nitrification, thus delaying the conversion process.

Introduction

Biochar can be added to the soil to help improve soil moisture retention (Glaser et al. 2002, Basso et al. 2013, Imhoff and Nakhli 2017, Trippe and Phillips 2018), reduce runoff (Imhoff and Nakhli 2017), increase soil sorption potential to limit chemical and nutrient losses via leaching to the groundwater (Tian et al. 2014, 2016), add carbon to the soil (biochar is carbon), and augment root penetration (Bruun et al. 2014). Biochar can also alter the microbial reactions in all phases of soil nutrient cycles (Gul and Whalen 2016). Moreover, biochar can increase crop yields (Jeffery et al. 2011, Biederman and Harpole 2013, Liu et al. 2013).

Biochar is basically a carbon product that is similar to charcoal or activated carbon but has its own unique set of properties. There are many different types of biochar created from different carbon sources (wood, sawdust, poultry litter, etc.) and using different methods of pyrolysis (burning). Biochar can be made simply in a primitive campfire or in a modern bio-refinery at different temperatures. The method of biochar production can affect its properties markedly; for example, pyrolysis biochar produced in the absence of oxygen can be hydrophobic (Suliman et al. 2017). Because there is such a wide range of biochar, the USDA created a database web-based decision support tool to help soil biochar users predict how a specific biochar could interact with specific soils (www.PNWbiochar.org).

Yield improvements with addition of biochar to agricultural soils have been documented (see Crop Yield section). However, Trippe and Phillips 2018 caution that biochar effects may not consistently occur in soils that are already well-managed, implying there might be more of an effect for marginal soils and marginal conditions. In this study, we are concerned with biochar effects on yields under irrigation, using potatoes grown in a loamy sand soil in central Washington as a model scenario, a soil condition under which the addition of biochar might offer some advantage.

Objective of the study

The objective of this study is to use a crop growth simulation model (CropSyst) to evaluate the long-term effect of various kinds of biochar, different application rates, and a few water supply regimes. Crop simulation is a useful tool because the model can eliminate the possibility of a dry or a wet year influencing an outcome by running the model over a period of many years and looking at the average results and their distribution.

For this study, we evaluated the potential effect of biochar in central Washington by simulating the growth of potatoes on a loamy sand soil under irrigated conditions. We evaluated the effect of biochar incorporated into the topsoil on dry yield, net irrigation (irrigation application losses not included), deep percolation, nitrogen applied, nitrogen leached, and nitrous oxide emissions. Nitrogen leached and nitrous oxide emissions are of interest as they relate to nitrogen losses that can have negative water quality and climate impacts, respectively.

CropSyst background

CropSyst is a multi-crop simulation model developed at the Washington State University and hosted at http://sites.bsyse.wsu.edu/cs_suite/CropSyst. Model descriptions are available in

Stöckle et al. (1994) and Stöckle et al. (2003), and some examples of applications are presented in Stöckle et al. (2014). The model uses a daily time step to evaluate simulation results over multiple years. CropSyst is an analytic tool that can be used to study the effect of cropping systems management on productivity and the environment. The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and erosion. Management options include: cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations, and residue management.

Kemarian and Stöckle (2010) extended the CropSyst model by adding a single-pool multi-layer carbon model (C-Farm). Simulating soil carbon cycling is important since carbon storage in the soil can play a role reducing the atmospheric CO₂ concentration. This carbon model has been coupled with the nitrogen model in CropSyst, which includes an ammonium sorption/desorption sub-model. Sorption is removal of a chemical from aqueous solution by partitioning a fraction of the chemical mass from the soil solution to the surface of soil solid particles while desorption is the release of a sorbed chemical back into the soil water solution. By maintaining an equilibrium between the chemical mass sorbed and in solution phases, the soil regulates the supply of ammonium and other positively-charged chemicals to the crop.

An advanced user-friendly interface allows users to easily manipulate input files, verify input parameters, create simulations, execute single or batch runs, customize outputs, and output text or graphical reports. Simulations can be customized to a sub-set of modules for a particular application producing more efficient runs and simplifying model parameterization. The model is currently written in C++ and is fully documented (Stöckle et al. 1994). The CropSyst executable program, manual, and tutorials can be retrieved: directly over the Internet from http://www.bsyste.wsu.edu/CS_Suite.

Biochar effects on agricultural soils

Physical properties

Biochar affects soil physical properties in many ways. In general, the bulk density is decreased, while the porosity, saturation and available water are increased, while the effect on saturated and unsaturated vertical hydraulic conductivity is mixed. Hydraulic conductivity measures the ease with which water moves downward through pore spaces or fractures.

Biochar particles are lighter (1.1-1.7 g/cm³) (Trippe and Phillips 2018) than the typical soil particles (2.65 g/cm³) (Rawls et al. 1982). When mixed into the soil, the bulk density is lowered in accordance with the percent biochar incorporated (Imhoff and Nakhli 2017). For example, incorporating 6% biochar by weight into loamy sand can change the bulk density from 1.6 to 1.2 g/cm³. This decrease in bulk density directly relates to an increase in soil porosity, although much of the porosity is internal to the biochar particles (intra porosity) and not directly related to the bulk porosity (inter porosity) that affect water retention (Imhoff and Nakhli 2017, Trippe and Phillips 2018). As bulk density decreases, root penetration increases with biochar addition (Bruun et al. 2014).

The measured effect of biochar on water retention, or the soil moisture characteristic curve (SMC), in the laboratory has been varied. In general, the increase in water content is higher for field capacity than wilting point, resulting in an increase in available water.

A review paper on the effect of charcoal in weathered tropical soils by Glaser et al. (2002), indicated 18% increase of available water was possible by adding 45% charcoal by volume. Basso et al. (2013) used a sandy loam to conclude that addition of up to 6% by weight biochar increased field capacity up to 23% with large increases on the wet end of SMC curve. and the effect increased with time. A pot study by Novak et al. (2012) found biochar enhanced , but the effect varied with the material used and pyrolysis temperature. Bruun et al. (2014) also used column experiments with a coarse sandy soil with poor water retention to find that in situ water content and wilting point increased linearly by 2.9% and 0.3% per 1% added biochar (% by weight), respectively. Ulyett et al. (2014) used a laboratory setting with organically and conventionally managed sandy loam soils to show that addition of biochar increased available water for both soils.

Gaskin et al. (2007), in a laboratory study on a Tifton loamy sand with biochar applications, showed no increase in available water for low application rates (equivalent of 11 and 22 t/ha) but the highest application rate (88 t/ha) doubled field capacity water content at moist end of SMC curve. No depth of mixing was provided to enable calculation of biochar content by weight. Sun and Lu (2014), using a clay soil in the laboratory, found that biochar amended soils exhibited significant increases in saturation water content, field capacity, wilting point, and available water. The available water of amended soils was 1.4%, 6.1%, and 18.4% greater than the control soil for the 2, 4, and 6% by weight biochar treatments. Tian et al. (2014) used laboratory experiments with sand and found that soil moisture increased with biochar content across the entire SMC. Imhoff and Nakhli (2017) performed laboratory experiments to amend three soils (loamy sand, sandy loam, and silt loam) with 2 and 6% by weight biochar. For 6% by weight biochar, they found that available water increased by 70, 20, and 25% for loamy sand, sandy loam and silt loam, respectively. The effect was mostly on the wetter end of the curve with little effect on wilting point. Suliman et al. (2017) using SMC measurements, found that over a wide range of soil water potentials, biochar mixtures held more water than the control soils except near saturation; this last result is an exception to most other studies. Trippe and Phillips (2018) using SMC equipment found that biochar mixed with sand and loamy sand increased saturation water content but not field capacity while biochar incorporated into silt loam and sandy loam has less consistent results.

Field experiment have had more varied results. Gaskin et al. (2007) found no significant differences in soil moisture contents with biochar amended soils at rates of 11 and 22 t/ha. Dugan et al. (2010) used field experiments with three biochar types (sawdust, corn stover, local charcoal) on three soils types (silt loam, sandy loam, and loamy sand) in Ghana at application rates up to 15 t/ha and found no effect on available water.

Biochar can reduce runoff which could enhance infiltration and soil water availability. Stormwater experiments using non-agricultural soils were performed by Imhoff and Nakhli (2017). Pilot-scale stormwater experiments on a sandy loam with 4% by weight biochar reduced runoff by 13% while field-scale stormwater experiments on a roadway filter strip amended with 4% by weight biochar reduced runoff and peak flow by about 50%. Runoff reduction effects were more pronounced at the field-scale than the laboratory scale. The effect of biochar on soil hydraulic conductivity is mixed. Imhoff and Nakhli (2017) found in laboratory experiments that unsaturated hydraulic conductivity increased with biochar addition but for saturated conductivity the results were mixed.

Chemical properties

Biochar also affects soil chemical properties in many ways. In general, the carbon content is increased, cation exchange capacity (CEC) is increased (Tian et al. 2016), soil pH is increased (Liu et al. 2013), and soil sorption of chemicals and nutrients is increased (Tian et al. 2016). The increase in CEC allows for a higher degree of adsorption that augments adsorption of Ca^{2+} , Mg^{2+} , Na^+ , NO_3^- , NH_4^+ , K^+ , and SO_4^{2-} (Strawn et al. 2015).

A review paper by Glaser et al. (2002) indicated that mixing relatively large amounts of hardwood charcoal with soil increased the CEC by 50% compared to control but even low amounts of weathered charcoal can increase CEC. In column studies, Gaskin et al. (2007) found that adding 0.5% by weight biochar to a Tifton loamy sand increased the CEC by 5% whereas Basso et al. (2013) found that addition of 3% and 6% by weight biochar to a sandy loam showed no increase of effective CEC. Tian et al. (2016) found that NH_4^+ sorption increased with CEC and that ion competition from calcium sometimes suppressed NH_4^+ sorption.

Chemical sorption can be modeled using isotherm data that are fit to the various isotherm models. The Langmuir isotherm equation below, implemented in CropSyst, can be used to define the shape of the adsorption curves. Because the aim of this study is to evaluate the effect of biochar addition on water and nitrogen, and ultimately on crop yields, we focused on the reported Langmuir parameters for ammonium in this review. The Langmuir isotherm curve is given as follows:

$$q_e = \frac{K_L C_e q_x}{1 + K_L C_e}$$

where q_e = equilibrium solute sorbed to soil (mg solute/kg soil)

C_e = equilibrium concentration of solution (mg/L)

K_L = Langmuir affinity parameter (L/mg)

q_x = maximum sorption capacity (mg solute/kg soil)

A number of studies have looked at NH_4^+ sorption for various biochars by quantifying the isotherm parameters. Yao et al. (2012) used sorption studies in a sandy soil with thirteen biochars that showed how widely biochar sorption characteristics can vary. Four biochars removed NO_3^- and NH_4^+ was adsorbed by nine biochars. Sarkhot et al. (2013) investigated NH_4^+ on biochars using dairy effluent; up to 5.3 mg/g NH_4^+ was adsorbed from manure solution. During desorption (< 24 h), 78-91% of the sorbed NH_4^+ was retained. Tian et al. (2014, 2016) conducted batch sorption experiments with biochars made from poultry litter and hardwood at various pyrolysis temps (400 and 500 C). Fidel et al. (2018) found that NH_4^+ sorption was maximized with low pyrolysis temperature (400 F) at near-neutral pH. Yang et al. (2018) determined adsorption of NH_4^+ to biochars made from pine sawdust and wheat straw at 300 and 550 C. In general, biochars made at low temperatures had more adsorption than those made at high temperatures and high pH increased adsorption. The Langmuir isotherm values from literature are summarized in Table 1.

Table 1. Biochar ammonium isotherm parameters from various studies

Source	Parameter	Biochar Sorption	
		Low	High
Sarkhot et al. (2013)	K _L (L/mg)	0.002	0.002
	Q _x (mg/g)	3.270	4.159
Tian et al. (2014)	K _L (L/mg)	0.226	0.199
	Q _x (mg/g)	0.113	0.566
Tian et al. (2016)	K _L (L/mg)	0.106	0.373
	Q _x (mg/g)	0.059	0.511
Yang et al. (2018)	K _L (L/mg)	0.025	0.100
	Q _x (mg/g)	2.080	3.370
Averages	K _L (L/mg)	0.090	0.168
	Q _x (mg/g)	1.380	2.151

Crop yield

Meta-analysis of yield responses to biochar addition to agricultural soils is a useful tool for analyzing the data from a variety of experimental conditions over many studies.

Jeffery et al. (2011) found that the mean yield increase due to biochar addition was 10%. They also found that the kind of biochar material greatly affect the yield response, ranging from biosolids (-28%) to poultry manure (24%). Better yield response was found in acidic (17%) and neutral (14%) soils with coarse (10%) or medium (13%) texture. The yield increase was least for cereals (4%) and greatest for vegetables (16%). Greater responses were found in pot experiments (16%) versus the field experiments (6%).

Biederman and Harpole (2013) focused on the response of above- and below-ground crop productivity to biochar application to soils. On average, biochar increased aboveground productivity and crop yield compared with control conditions. Soil pH also tended to increase, becoming less acidic, following the addition of biochar. No detectable relationship was found between the amount of biochar added and aboveground productivity.

Liu et al. (2013) found that for amendment rates <30 t/ha, biochar increased crop productivity on average by 11%. Greater responses were found in acid versus neutral soils, in sandy versus loam or silt textured soils, and in pot versus field experiments. Crop response in field experiments was greater for dryland crops (11%) than for paddy rice (6%).

Gul and Whalen (2016) provide a good summary of yield effect of biochar in Tables 1 and 2 of their paper. We have extracted the field studies for those studies where control and biochar treatments were similarly fertilized. Many of the studies are in acidic conditions, which seems to respond to the liming characteristics of biochar, favoring yield increase. A summary of these yield studies is given in Table 2.

Table 2. Crop yield response to biochar amendment for field experiments
(modified from Gul and Whalen, 2016)

Biochar (BC)	BC Rate (t/ha)	Soil Texture	Soil pH	N/P Rate (kg/ha)	Crop	Yield (t/ha)	Yield Increase (%)		
Debarked spruce chips (500-600 C)	0	Clay loam	6.6	0/0	Faba bean	3.32			
	5					3.27	1.51		
	10					3.28	1.21		
Willow wood (550 C)	0	Clayey	5.6	34.5/37.5	Maize	7.14			
	10					9.21	22.5		
Biochar 1st year	0	Clay loam	3.9	165/43	Maize	5			
	8					5	0		
	20					5	0		
Biochar 2nd year	0			170/33		5			
	0					6	17		
	0					6.5	23		
Biochar 3rd year	0			156/30		5.8			
	0					6.7	14		
	0					7.8	25.4		
Biochar 4th year	0			159/30		5.8			
	0					6.7	14		
	0					7.8	25.4		
Willow wood (550 C)	0	Loamy sand	6.2	26.6/31.6	Peanut	4.17			
	10					5.05	17.5		
Wood residue (350-550 C)	0	Clay loam	5.4	0/0	Rice	0.7			
	8					0.8	12.5		
	18					0.7	0		
	0	Loam				3.8			
	8		4	5					
18					3.7	-2.6			
Beech wood	0	Silt loam	7.4	120/0	Spring	5.5			
	24					5.4	-2		
	72					6	8.4		
Coppiced woodlands (500 C)	0	Silty sand	5.2	122/50	Wheat	2.28			
	30					2.92	22		
	60					2.93	22.2		
Coppiced woodlands (500 C) 2nd year	0					2.4			
	0					3.19	24.7		
	0					3.34	28.1		
Olive tree pruning (450 C)	0	Clay loam	8.2	110/0	Wheat	4.42			
	40					5.61	21.22		
Debarked spruce chips (500-600 C)	0	Loamy sand	4.6	63.4/0	Wheat	3.8			
	5					3.5	-8		
	10					3.6	-5.3		
	20					3.4	-10.5		
	30					4.1	-7.9		
Wheat straw (400 C)	0	Silt clay	5.1	0/0	Amaranth	20			
	20					23	13		
	40					20	0		
	0						130.3/130.	15.8	-21
	20							23.5	15
	40							34	42.2
Wheat straw (400 C)	0	Silt clay	5.1	0/0	Baby Bok	20			
	20					35	43		
	40					59	66.1		
	0						145/145	23	13.1
	20							25	20
40				40	50				

Model input parameters

Agricultural soil

Values for bulk density, wilting point, field capacity, and saturation water content for loamy sand were used from Imhoff and Nakhli (2017). The Campbell parameters for the loamy sand SMC were derived from the wilting point, field capacity, and saturation values. Langmuir adsorption isotherm values for loamy sand were based on batch adsorption experiments performed on New Zealand agricultural soils (Vogeler et al. 2011). These parameters are listed in the Column labeled “Loamy Sand” in Table 3.

Soil mixes

The physical parameters for soil mixes with biochar (2% by weight and 6% by weight) were based on observed values for the loamy sand used in Imhoff and Nakhli (2017). The two biochar mixes for a loamy sand with a bulk density of 1.6 g/cm³ (Table 3) correspond to biochar application rates of 96 t/ha and 288 t/ha for 2% by weight and 6% by weight mixes, respectively.

Langmuir adsorption isotherm coefficients were extracted from the summary in Table 1. We used the average low value and average high values from these studies. The last four lines in Table 3 are the weighted average of loamy sand mixed with biochar (2% and 6% by weight) using both the low and high averages for K_L and q_x .

The relative changes of soil parameters are given in Figure 1 and Figure 2.

Table 3. Soil parameters used in CropSyst model scenarios; BC = biochar

Parameter	Material	Loamy Sand	Loamy Sand + 2% biochar (w/w)	Loamy Sand + 6% biochar (w/w)	Comment
Bulk density (g/cm ³)	Soil mix	1.60	1.40	1.20	Imhoff and Nakhli (2017)
Wilting point (cm ³ /cm ³)	Soil mix	0.04	0.04	0.04	Imhoff and Nakhli (2017)
Field capacity (cm ³ /cm ³)	Soil mix	0.13	0.15	0.18	Imhoff and Nakhli (2017)
Saturation (cm ³ /cm ³)	Soil mix	0.43	0.48	0.52	Imhoff and Nakhli (2017)
Campbell β (-) ¹	Soil mix	2.90	2.84	2.53	Derived
Campbell Ψ_e (kPa) ²	Soil mix	1.00	1.32	2.27	Derived
NH ₄ K (L/mg)	Soil mix with low	0.001	0.003	0.006	Interpolated
NH ₄ Qmax (mg/g)	Soil mix with low	3.30	3.26	3.18	Interpolated
NH ₄ K (L/mg)	Soil mix with high	0.001	0.004	0.011	Interpolated
NH ₄ Qmax (mg/g)	Soil mix with high	3.30	3.28	3.23	Interpolated

¹ β = coefficient in the Campbell (1985) equation for soil water retention

² Ψ_e = air entry potential in the Campbell (1985) equation for soil water retention

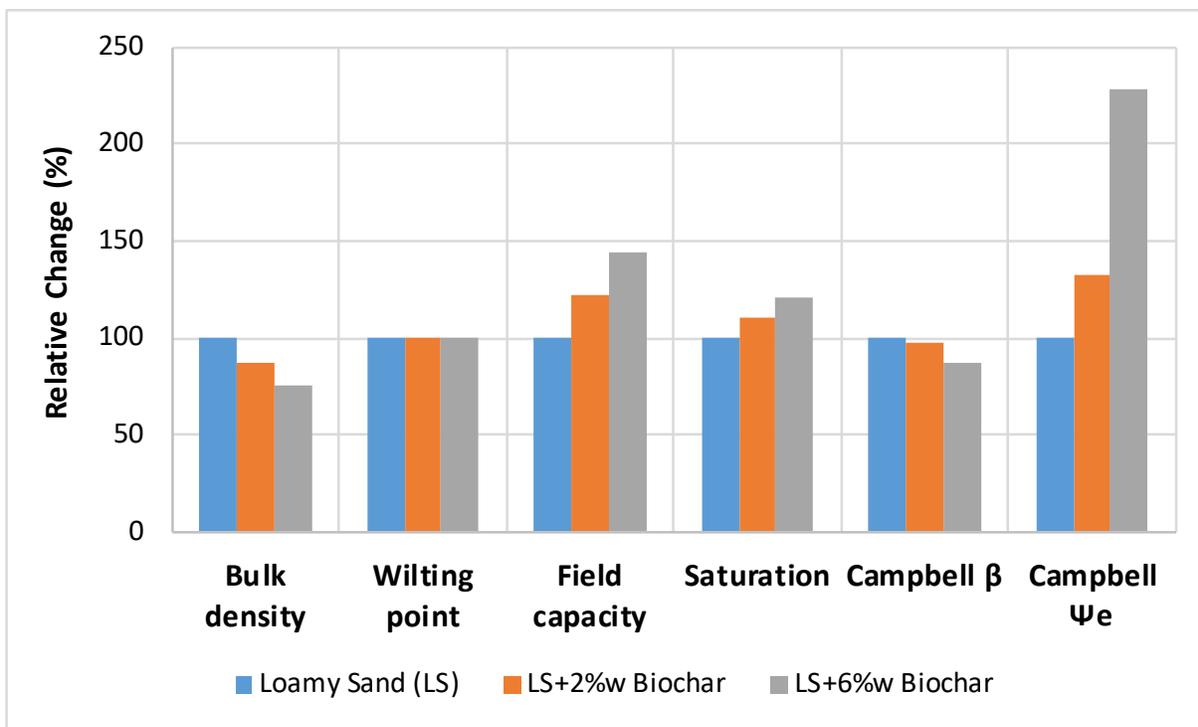


Figure 1. Change in physical parameters for CropSyst biochar simulations

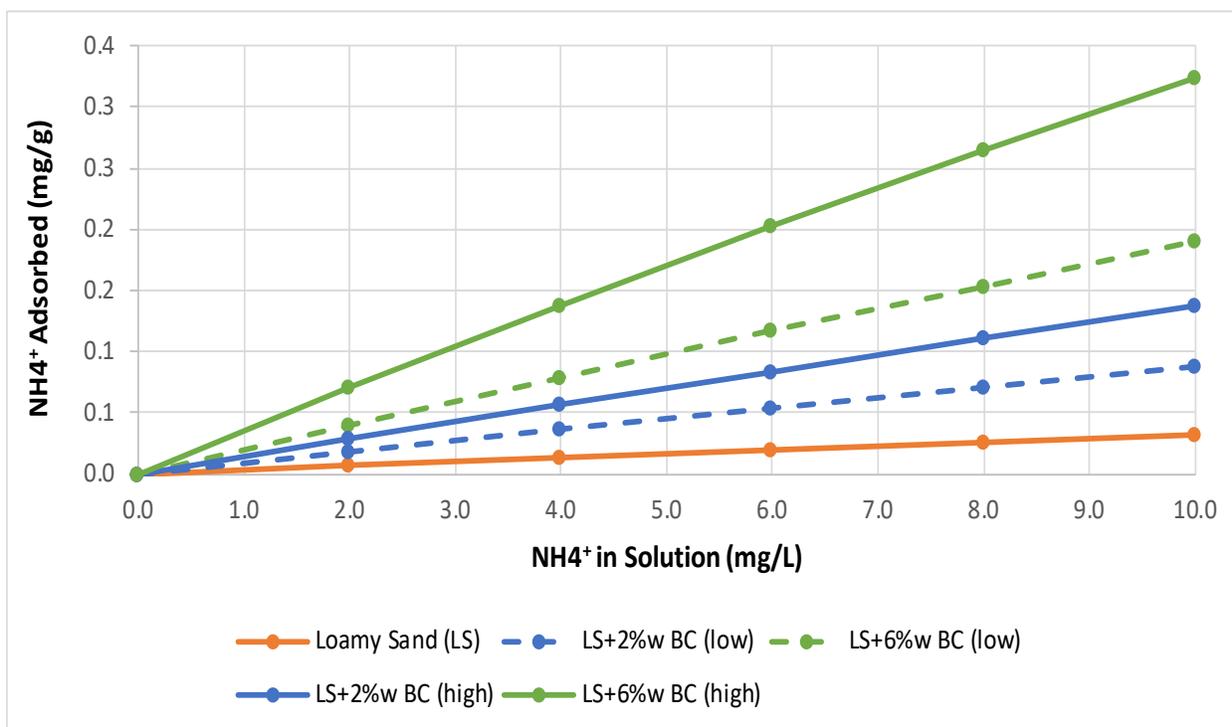


Figure 2. Change in sorption curves in CropSyst biochar simulations; BC = biochar

Model scenarios

The CropSyst model was set up to simulate growing potatoes on a loamy sand soil in the climatic region of central Washington State near Moses Lake, Washington. There were 5 different soils (loamy sand plus 4 mixes of loamy sand + biochar) and three different irrigation schemes (full, deficit, and no irrigation) to give a total of 15 runs. Thirty-year simulations (1981-2010) provided weather variability to the 15 scenarios.

The kind of biochar and application rate changed the soil moisture and ammonium adsorption parameters of the top 30 cm of soil. The water supply regime changed the irrigation amount. Nitrogen application was adjusted for each run to avoid crop nitrogen deficiency (as reported by the model). Scenarios are given in Table 4.

Table 4. Summary of CropSyst model scenarios

Model Run	Irrigation	Soil	% Biochar (w/w)	Biochar Applied (t/ha)	Type of Biochar
FI-LS	Full	Loamy Sand	0	0	None
FI-BL2	Full	Loamy Sand	2	96	Low adsorption
FI-BL6	Full	Loamy Sand	6	288	Low adsorption
FI-BH2	Full	Loamy Sand	2	96	High adsorption
FI-BH6	Full	Loamy Sand	6	288	High adsorption
DI-LS	Deficit	Loamy Sand	0	0	None
DI-BL2	Deficit	Loamy Sand	2	96	Low adsorption
DI-BL6	Deficit	Loamy Sand	6	288	Low adsorption
DI-BH2	Deficit	Loamy Sand	2	96	High adsorption
DI-BH6	Deficit	Loamy Sand	6	288	High adsorption
NI-LS	None	Loamy Sand	0	0	None
NI-BL2	None	Loamy Sand	2	96	Low adsorption
NI-BL6	None	Loamy Sand	6	288	Low adsorption
NI-BH2	None	Loamy Sand	2	96	High adsorption
NI-BH6	None	Loamy Sand	6	288	High adsorption

Results and discussion

Although the addition of biochar to the top 0.3 m of the soil increased the soil water holding capacity from 25 mm (loamy sand) to 34 mm (2% by weight biochar) to 42 mm (6% by weight biochar) in the top 0.3 m of soil, under full irrigation (Table 5) the effect of biochar addition on potato yields was negligible (Figure 3). Although modest, the effect of biochar addition was noticeable under deficit irrigation and no irrigation treatments where it resulted in a yield increase of about 4% (Table 5; Figure 3). These results are consistent with yield increases reported in the literature for dryland cereal crops, which are in the range of 0 to 8%, with an

average of 4 to 5%. They also indicate that based on the mechanisms modeled, the addition of biochar to irrigated crops under full irrigation is unlikely to be advantageous unless acidic conditions are improved by biochar additions, a process currently not simulated by the model. Yields of dryland crops grown in the Inland Pacific Northwest might benefit, particularly when applied at high rates, although the economic benefit of biochar addition will require evaluation, as dryland crops are lower value per acre than irrigated crops.

Table 5. Scenario results

Scenario	Dry Yield (kg/ha)	Net Irrigation* (mm)	Deep Percolation (mm)	N Applied (kg/ha)	N Leached (kg/ha)	N₂O-N Emission (kg/ha)
FI-LS	16,302	676	10.4	309	6.7	1.4
FI-BL2	16,305	683	9.9	308	6.9	1.6
FI-BH2	16,305	683	9.9	308	6.9	1.6
FI-BL6	16,308	694	10.7	308	7.8	1.6
FI-BH6	16,308	694	10.7	308	7.8	1.7
DI-LS	14,524	524	1.2	290	1.7	1.2
DI-BL2	14,815	530	0.7	293	0.9	1.3
DI-BH2	14,815	530	0.7	293	0.9	1.3
DI-BL6	15,145	531	0.4	296	0.6	1.4
DI-BH6	15,145	531	0.4	296	0.6	1.4
NI-LS	2,123	0	0.7	117	2.1	0.7
NI-BL2	2,171	0	0.4	118	1.1	0.7
NI-BH2	2,171	0	0.4	119	1.1	0.7
NI-BL6	2,208	0	0.3	117	0.9	0.8
NI-BH6	2,209	0	0.3	117	0.9	0.8

* Seasonal precipitation average was 64 mm

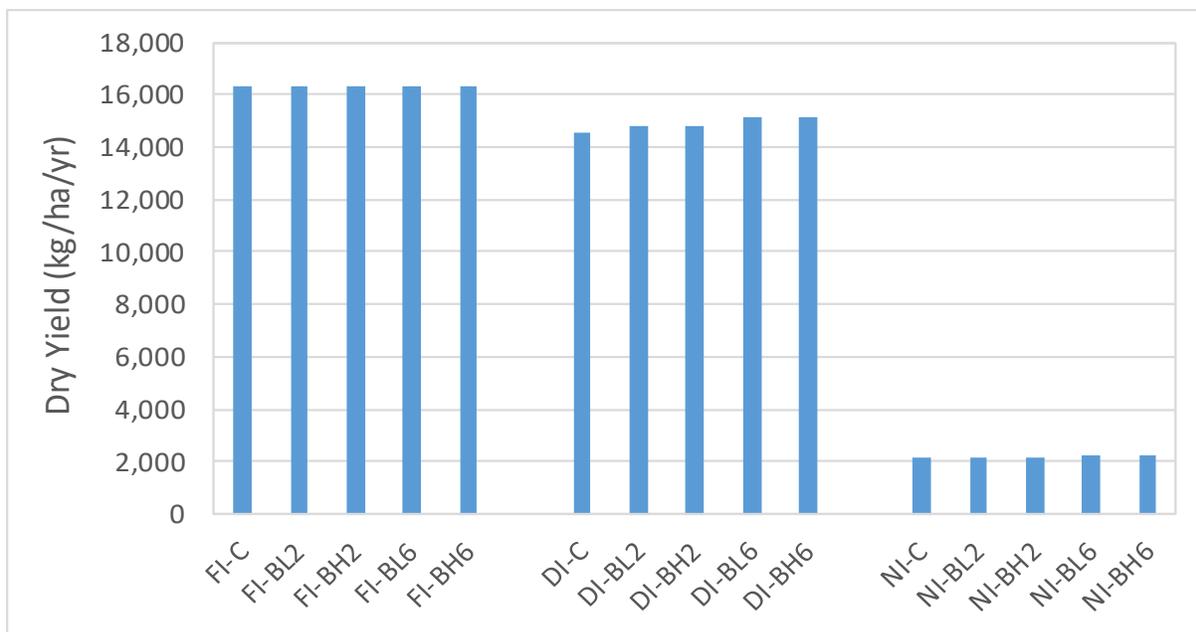


Figure 3. Potato dry yield for different CropSyst scenarios

On average, the net amount of irrigation water applied was essentially not affected by biochar addition, with small increases linked to the small yield gains (Table 5; Figure 4). Net irrigation demand is rather determined by weather and crop growth. Similarly, biochar addition did not substantively affect water drainage below the root zone depth (deep percolation), while deep percolation clearly decreased with deficit and no irrigation (Figure 5).

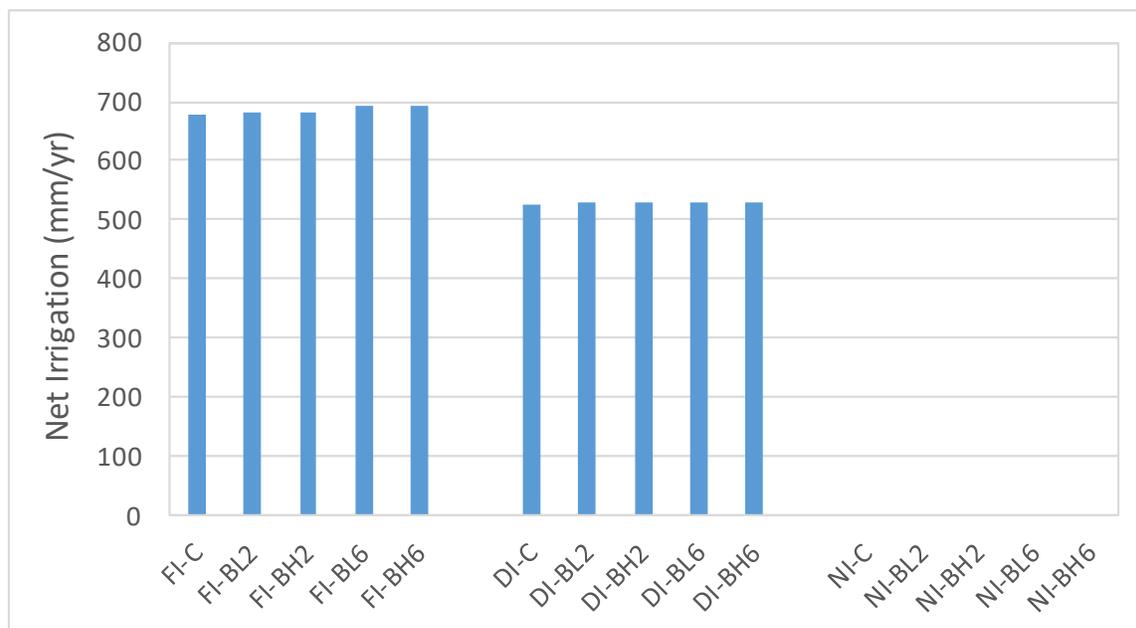


Figure 4. Net irrigation depth required for different CropSyst scenarios

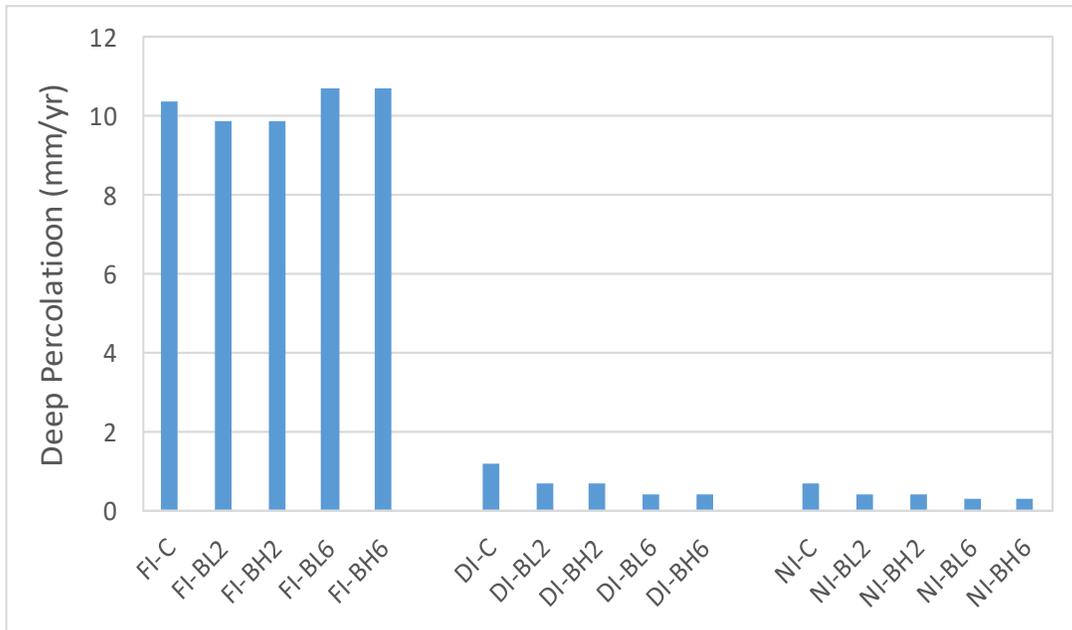


Figure 5. Deep percolation for different CropSyst scenarios

The amount of ammonium nitrogen applied to each treatment is shown in Figure 6. These amounts are calculated by CropSyst to ensure that the crop in all treatments is not nitrogen deficient. Nitrogen leaching, as expected, decreased with reductions in irrigation applied and deep percolation (Table 5; Figure 7). Biochar addition slightly increased the amount of N leaching under full irrigation and the higher biochar mix of 6% by weight, but biochar addition tended to slightly decrease N leaching for the deficit irrigation and no irrigation treatments. These are not important differences, and they are partially due to small yield differences and concurrent nitrogen uptake changes, and partially the result of interactions between irrigation and fertilization timing and amounts calculated by the model. Overall N leaching and water deep percolation were correlated as expected. The increase of ammonium sorption with biochar addition did not impact N leaching because microbial activity converts ammonium to nitrate relatively fast. While ammonium transport is minimal in the soil profile due to adsorption, nitrate does not interact with soil particles and the biochar and it is readily available to be transported by water and subjected to leaching beyond the reach of potato roots. It is unclear if biochar can offer an increased degree of protection against the microbial activity leading to nitrification; however, the additional surface area from biochar at the mixing rates normally used is small compared to the bulk soil.

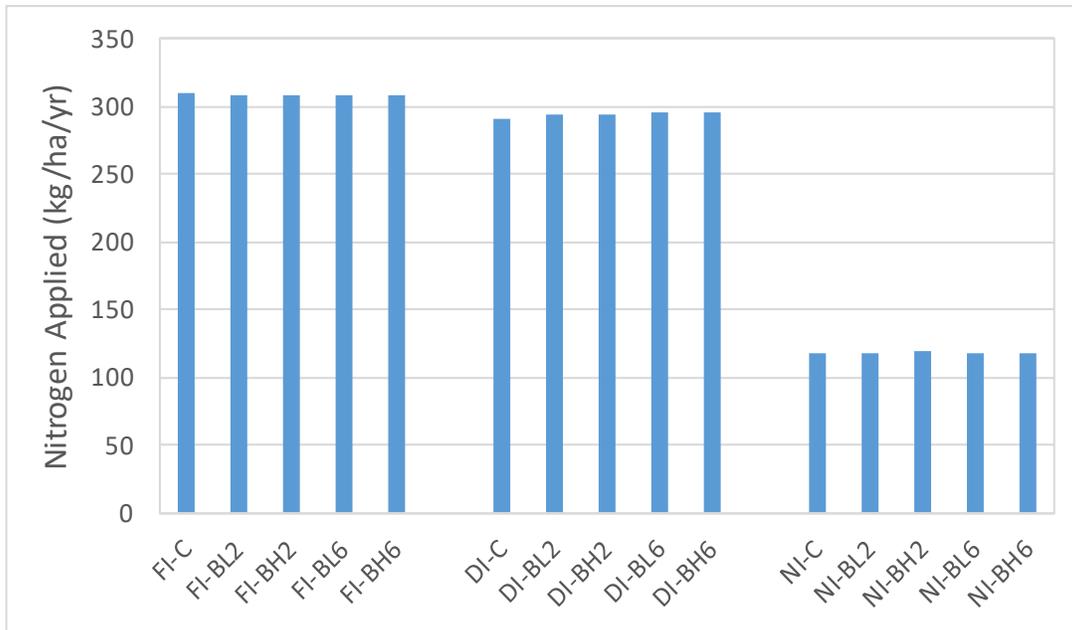


Figure 6. Nitrogen applied for different CropSyst scenarios

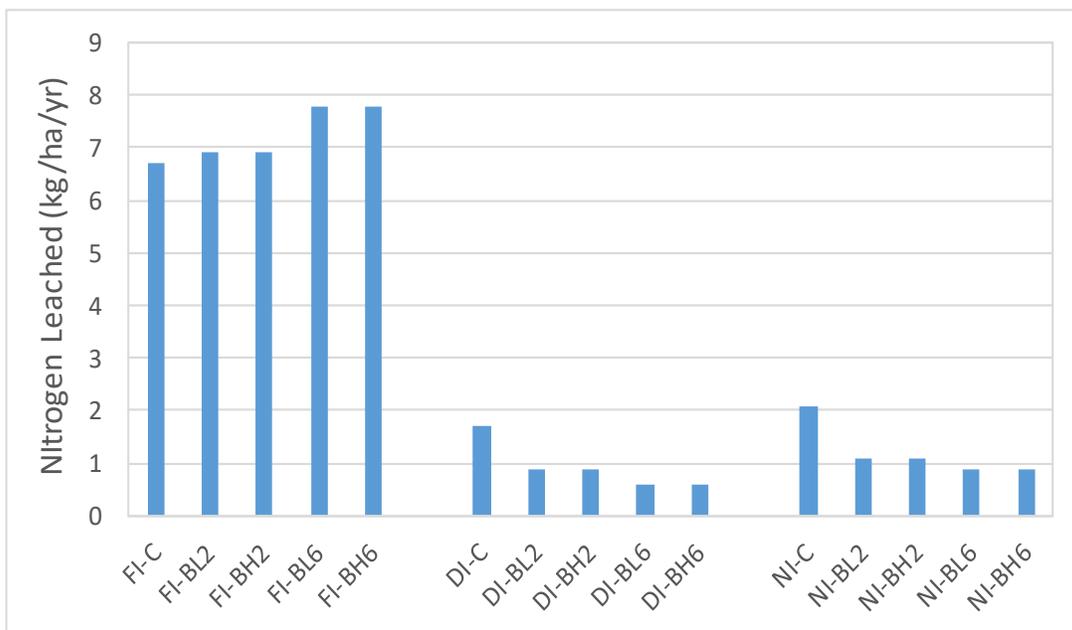


Figure 7. Nitrogen leached for different CropSyst scenarios

The emissions of nitrous oxide (N_2O), a powerful greenhouse gas affecting climate change, were proportional to the amount of ammonium fertilizer applied, decreasing in the order FI > DI > NI (Table 5; Figure 8). For the loamy sand soil considered in this study, that drains fast and does not provide opportunities for soil saturation leading to denitrification (a major process enhancing N_2O emissions), the bulk of the emissions came from nitrification, the conversion of ammonium

to nitrate, and thus they were related to the amount of ammonium fertilizer applied (Figures 6 and 8). The addition of biochar, and more so when biochar application rates were increased from 96 to 288 t/ha, slightly increased N₂O emission in all irrigation treatments. Because this effect was not related to the biochar ammonium adsorption capabilities (BL and BH for a given application rate were not different), it points more to a water holding capacity increase effect creating slightly better conditions for microbial activity.

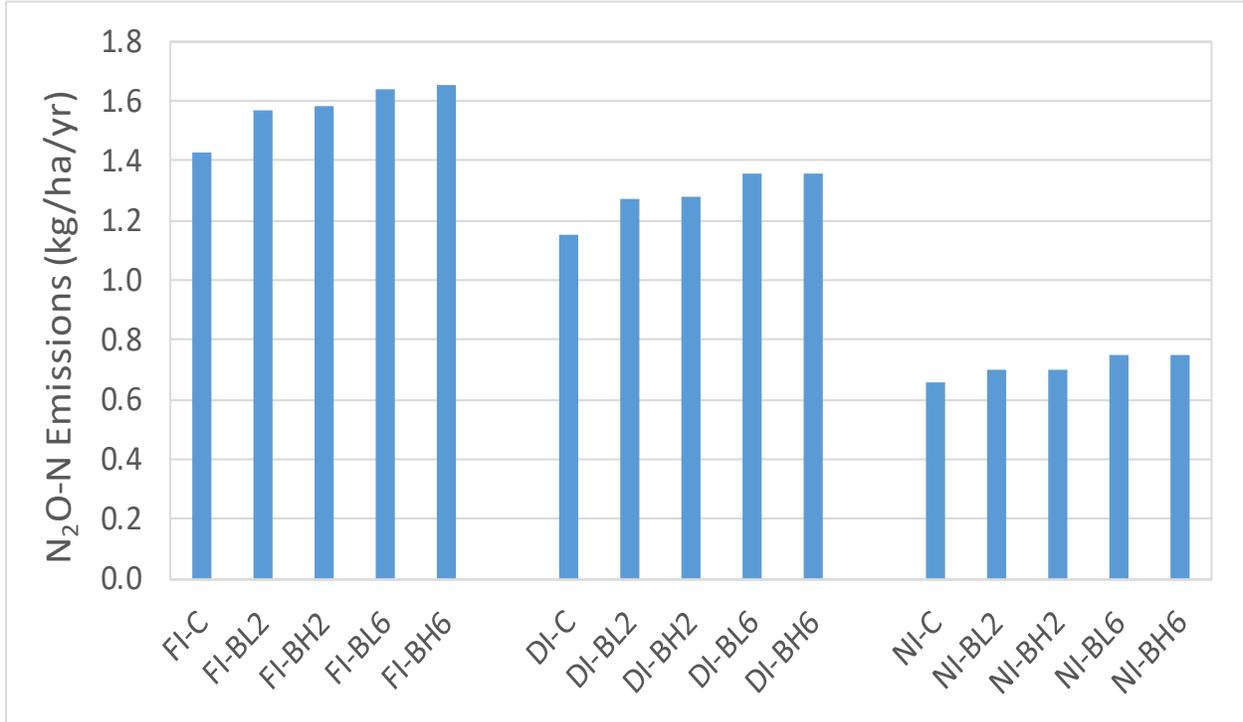


Figure 8. Nitrous oxide emission for different CropSyst scenarios

Irrigation and nitrogen management was uniform and near optimum in these simulations. Actual field conditions most likely will experience greater differences in water drainage, N leaching, and N₂O-N emission due to non-uniform soil and topographic conditions, which will lead to non-uniform irrigation and fertilizer applications. Overall, field conditions are likely to result in more yield variation within fields and mask the small effect of biochar addition estimated by the computer simulations presented in this study.

Summary and conclusions

A computer simulation study was conducted to evaluate the potential effect of biochar addition to a loamy sand soil with low water holding capacity, with the expectation that two biochars (high and low ammonium adsorption) added at rates of 96 and 288 t/ha and mixed to a soil depth of 0.3 m (resulting in much larger application rates than usually reported) would increase water retention, decrease nitrogen losses, and increase yields of potatoes. The simulations considered full irrigation, deficit irrigation, and no irrigation treatments and covered a period of 30 years using weather data from a location near Moses Lake, WA.

It was found that the effect of biochar on potato yields was negligible under full irrigation, but with small gains of ~4% when water was limiting (deficit and no irrigation treatments). Full irrigation assumes that plants receive irrigation sufficient to meet evapotranspiration demand and achieve maximum yields, so it would not incorporate the benefits of additional water holding capacity when water supply is limiting yields. This result is consistent with dryland cereal crop experiments reported in the literature, when conducted in agricultural soils not limited by low pH or low fertility. Based on the physical and chemical mechanisms modeled, the addition of biochar to fully irrigated crops is unlikely to improve yields unless acidic conditions are improved by biochar additions. However, yields of dryland crops grown in the Inland Pacific Northwest might benefit, particularly when applied at high rates, although the economic benefit of biochar addition will require evaluation, as dryland crops are lower value per acre than irrigated crops.

Regarding nitrogen, the relatively fast conversion of ammonium to nitrate (nitrification) neutralized the effect of the additional ammonium sorption capabilities provided by biochars, providing no advantage. It is unclear if biochar can provide a degree of physical protection against the microbial activity responsible for nitrification, thus delaying the conversion process.

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