McKinsey & Company

Methodological appendix and co-benefits results

January 2021

Contents

Methodological appendix

Disclaimer: Methodology was developed by McKinsey & Company's Nature Analytics solution, which builds on peer-reviewed methodologies and existing data points or spatial data layers. Although our geospatial analytics can provide useful directional guidance at global scale, drawing any local conclusions will require additional detailed, local studies, notably to include precise local geographic contexts or recent local developments (political or otherwise). In particular, analysis of costs of CO_2 abatement are country-level estimates primarily based on expert interviews aiming at providing directional information on costs. Any project-specific assessment should require additional, site-specific research.

Sizing the 'practical' carbon abatement potential of natural climate solutions

In this report we estimate the carbon abatement potential of eight Natural Climate Solutions (NCS) per year by 2030: reforestation, avoided deforestation, coastal restoration, avoided coastal degradation, peatland restoration, avoided peatland degradation, trees in cropland and cover crops.

For each NCS, the total solution potential is assessed via NCS-specific modeling, the granularity of which depends on the available data. Where available, geospatial data on the extent of targeted ecosystems (such as tropical forests and wetlands) and their degradation status allows assessment of where each NCS can be implemented by avoiding further degradation or restoring ecosystems. This is then combined with an estimate (geospatial or not) of the CO_2 sequestration potential of the NCS (or avoided emissions).

From the total potential, the "practical" abatement potential is then estimated for each NCS based on agricultural rent: areas with low (less than or equal to $10 per hectare) to medium (greater than $10 per hectare and less than or equal to $45 per hectare) agricultural rent. Agricultural rent is defined here as the economic return from agricultural land. The agricultural rent represents a key decision factor in land-use choices relevant to NCS and it is accounted for in most studies on NCS costs. It has been calculated as follows:

— We took granular crop yield and distribution for more than 40 main crops[1] and livestock weight and density for eight major livestock categories.[2]

— We derived granular gross agricultural revenue by matching yields with farm-gate prices of these crops and livestock.

— We used the ecoregion gross agricultural revenue median as the relevant ecoregion agricultural rent, to filter out extreme values and fill areas where no cropland is currently present, effectively assigning a hypothetical agricultural rent to land uses that are not (yet) converted to agriculture such as forests.

— We assumed 30 years of agricultural revenues discounted at 10 percent annually, a rate that is typically used by development banks for evaluating public investments in developing countries.

[1] The UN Food and Agriculture Organization (FAO)/MapSPAM
[2] FAO Global Gridded Livestock of the World

— We applied revenue to each area selected for NCS based on highest-revenue yielding crop in that area.

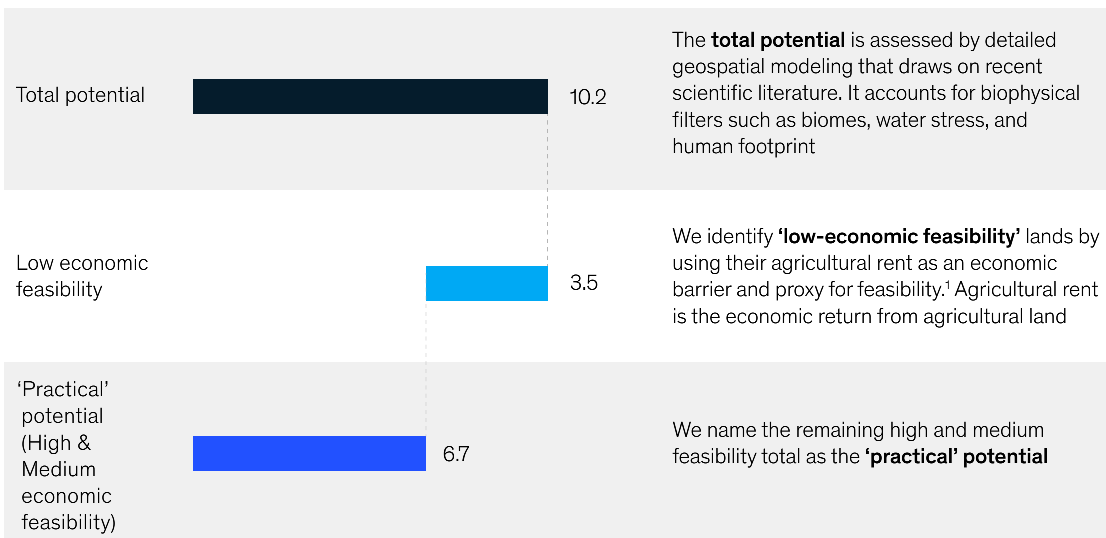
— We used statistical thresholds of $10 and $45 per hectare per year to differentiate between high and medium, and medium and low feasibility, corresponding to the 33rd and 66th percentiles of the ecoregion median values.

In summary, our total potential for the NCS sized is 10.2 gigatonnes (Gt) CO_2 per year. This total is then filtered down to our "practical" potential of 6.7 Gt CO_2 per year, which excludes low feasibility lands and includes medium and high feasibility lands as per our agricultural rent methodology above (Exhibit 1).

Exhibit 1

The 'practical' carbon abatement potential of NCS is 6.7 gigatonnes (Gt) CO_2 per year by 2030.

Abatement potential of NCS per year by 2030, Gt CO_2



The 'practical' potential is a portion of the total potential of NCS credits, in recognition that it becomes progressively more difficult to secure carbon credits as the total potential of each source is approached. It filters out "low economic feasibility" lands, which are more likely to be accessed by mechanisms other than voluntary carbon markets, such as philanthropic or governmental grants.

For example, the 'practical' potential of reforestation is sized at 1.0 Gt CO_2 per year by 2030, which excludes an additional 1.1 Gt CO_2 per year that is "low" feasibility according to our filter.

[1]Used statistical thresholds of $10 and $45/ha per year to differentiate between respectively high and medium, and medium and low feasibility, corresponding to the 33rd and 66th percentiles of the ecoregion median values.

Determining costs of natural climate solutions

Country-level cost curves were built for each NCS focusing on high-potential countries. NCS project costs were determined via expert interview and literature review, and discounted using a 10 percent discount rate on 30-year projects (in line with the academic literature) to account for the different time horizons of expenses.

Four types of cost are considered in our assessment:

— *Land costs:* The cost of acquiring or renting the area of land on which the NCS is developed plus any other land-related cost (such as land taxes).[3] For each country assessed, two cost estimates were provided: one for high feasibility (low cost) areas and one for medium feasibility (medium cost) areas. We assumed that cost differences in these areas were driven by land cost difference, which is highly correlated with the agricultural rent. For high feasibility areas, we therefore used the land cost provided by local expert (triangulated with local/official data sources) assuming that existing projects (on which experts base their information) were implemented in such high feasibility areas. For medium feasibility areas, we derived estimates of land value from a World Bank analysis.[4] One simplifying assumption taken was that project developers would be leasing land directly and paying land costs in full, rather than with the help of governments and non-profits, meaning at low to no cost.

— *Initial project costs:* The initial costs and investments needed to start an NCS project, including project and site preparation, site set-up, administration, and legal costs.

— *Recurring project costs:* The payments for labor, materials and overhead necessary to operate an NCS project throughout its duration, such as maintenance, administration, security, and community payment.[5]

— *Carbon credit monetization costs:* The cost of converting realized NCS impact into actual carbon credits. Detailed cost components included are: initial validation costs, annual verification costs,[6] and issuance fees. This does not include marketing costs.

Deep dives

Reforestation

We started by creating a map of global reforestation potential, following Bastin et al.[7] To do so, we first predicted tree coverage globally under natural conditions, independently of land-use. Based on the Bastin et al. data set on observed tree coverage within protected areas (78,774 photo-interpreted measurements), we trained a Random Forest model[8] using a set of spatial predictors at a resolution of one square kilometer grouped in four categories:

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[3] Land ownership structures (for example, communal land) mean that land used for an NCS might not be effectively acquired or rented at a market price. We still include the land value in our costs in those cases, as a proxy for the land opportunity costs.
[4] Glenn-Marie Lange, Quentin Wodon, and Kevin Carey, *The Changing wealth of nations 2018: Building a sustainable future*, Washington, DC: The World Bank, 2018. When World Bank values were either below or one order of magnitude larger than the prices for high-feasibility locations, we replaced them using a price-correlation equation.
[5] Using a standardized $ per hectare rate for countries outside Europe, North America, and Australia, based on expert inputs and a review of the academic literature.
[6] This can be every other year or up to every 5 years depending on the certification organization.
[7] Jean-Francois Bastin et al., "The global tree restoration potential," *Science*, July 5, 2019, Volume 365, Number 6448, pp. 76–9.
[8] Leo Breiman, "Random forests," *Machine Learning*, October 2001, Volume 45, Number 1, pp. 5–32.

— *Climate variables:*[9] Mean annual temperature, mean temperature in the wettest quarter, annual precipitation, precipitation seasonality, and precipitation in the driest quarter

— *Topographic variables:*[10] Slope, elevation, and hill shade

— *Soil variables:*[11] Bedrock depth, sand content, and World Reference Base soil classes

— *Biogeographic variables:*[12] Biomes and continent

Hyperparameter tuning was made using R's caret package[13] and repeated cross-validation with 40 folds and setting the number of trees at 500.

After transforming tree cover to forest cover, according to the definition of the Food and Agriculture Organization (FAO) of the United Nations,[14] we calculated the technical reforestation potential as the difference between the predicted forest cover and the current forest cover.[15]

The "realistic" reforestation potential is then calculated by filtering the technical abatement potential using three biophysical exclusion filters:

— *Biome filter:* For each NCS, we excluded biomes where the solution is non-natural or could have negative effects on ecosystems and climate, i.e. boreal forests/taiga; grasslands, tropical savannas, and shrublands; and deserts and xeric shrublands biomes.[16]

— *Water stress filter:* Based on data from the World Resource Institute, we excluded areas where water stress is projected to be extremely high (greater than 80 percent) or to be arid in 2040, based on the RCP 8.5 scenario.

— *Human footprint filter:* We excluded current cropland and urban areas,[17] as well as areas where urban expansion is projected with a probability greater than 50 percent by 2050.[18]

— Finally, we combined the reforestation map with state-of-the art geospatial data on CO_2 sequestration rates following natural regrowth[19] to compute the total potential CO_2 abated through reforestation for the next 30 years.

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[9] Stephen E. Fick and Robert J. Hijmans, "WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas," *International Journal of Climatology*, May 15, 2017, Volume 37, Number 12, pp. 4302–15.
[10] Derived from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, US Geological Survey, usgs.gov.
[11] Tomislav Hengl et al., "SoilGrids250m: Global gridded soil information based on machine learning," *PLoS ONE*, February 16, 2017, Volume 12, Number 2.
[12] David M. Olson et al., "Terrestrial ecoregions of the world: A new map of life on Earth," *BioScience*, November 2001, Volume 51, Number 11, pp. 933–8.
[13] Max Kuhn, "Building predictive models in R using the caret package," *Journal of Statistical Software*, November 10, 2001, Volume 28, Number 5.
[14] Land of at least 0.5 hectares with at least 10 percent tree cover.
[15] Derived from Marcel Buchhorn et al, "Fractional forest cover layer," 2019, Copernicus Global Land Service, Land Cover 100M: Epoch 2015, Globe (version 2.0.2).
[16] Following Joseph W. Veldman et al., "Comment on 'The global tree restoration potential,'" *Science*, October 18, 2019, Volume 366, Number 6463, we excluded trees planted in boreal forests, tundra, and montane grasslands and shrublands, which can have a negative net warming effect due to a decrease of albedo. Similarly, we excluded savannas and grasslands biomes, as tree planting in these regions will likely threaten biodiversity, through habitat replacement and increased fire risk, and reduce food security for locals relying on them for livestock forage, hunting, or water supply.
[17] Land cover classes 10, 20, and 190, from Marcel Buchhorn et al., "Copernicus Global Land Service: Land Cover 100m, collection 2: epoch 2015: Globe," *Zenodo*, 2019, Version V2.0.2 [Data set].
[18] Guangzhou Chen et al., "Global projections of future urban land expansion under shared socioeconomic pathways," *Nature Communications*, January 27, 2020, Volume 11, Article Number 537, nature.com.
[19] Susan C. Cook-Patton et al., "Mapping carbon accumulation potential from global natural forest regrowth," *Nature*, September 23, 2020, Volume 585, pp. 545–50.

— Our underlying assumption here is that reforestation follows a “plant and leave it” approach, rather than a plantation approach. As such, our sequestration rates and costs assume that any hectare of land will only be planted once.

To calculate reforestation project costs, we assumed reforestation projects aimed at replicating natural forests rather than purely commercial plantations. As such, all forestry management costs[20] (and revenues) typically associated with commercial plantations are excluded. This simplifying assumption was made to: (i) build a cost estimate on “higher quality” reforestation carbon credits, meaning those with the most co-benefits in terms of biodiversity; (ii) be consistent across countries by having one archetype of reforestation approach; and (iii) step away from the ongoing debate on whether commercial plantations are less “legitimate” as a result of commercial uses. For simplification, we assumed all planting takes place in year one.

Avoided tropical deforestation and peatland degradation

We relied on Busch et al.[21] to estimate areas that are likely to be deforested and associated CO_2 emissions in the tropics by 2050.[22] Their approach is based on a gridded land-cover change model accounting for site characteristics such as slope, elevation, protected status, initial forest cover, and agriculture revenue potential. We reproduced their results using provided codes and input layers.[23] Busch et al. project 541.5 million hectares (Mha) of deforestation between 2020 and 2050 under business as usual (BAU) (18 Mha per year), corresponding to 256.9 Gt CO_2. These estimates include deforestation of peat swamp forests and the resulted emissions from peatland loss. They exclude deforestation of mangrove forests and deserts.

Contrary to other NCS types, we used the work of Busch et al. to define the achievable potential using their Marginal Abatement Curves (MAC),[24] using thresholds of $10 per total carbon dioxide (tCO_2), $45 per tCO_2 and $100 per tCO_2 to differentiate between respectively high and medium, and medium and low feasibility. At $100 per tCO_2, replication data shows a total potential of 5.3 Gt CO_2 per year, while at $45 per tCO_2 and $10 per tCO_2, the potential is reduced respectively to 3.36 and 1.0 Gt CO_2 per year.[25]

To calculate avoided deforestation and peatland degradation project costs, we used our standard cost methodology using the same land value as for reforestation projects.

Coastal restoration and avoided degradation

We calculated the carbon abatement potential associated with the restoration and avoided degradation of coastal wetlands (focusing on mangroves and seagrass beds, which jointly represent at least 70 percent of global coastal wetlands).[26] The extent of avoided coastal impact is a combination of the extent of coastal ecosystems with restoration and with avoided degradation potential (mangroves[27] and seagrasses), both of

[20] E.g., fertilization, pruning and thinning of trees, etc.
[21] Jonah Busch et al., “Potential for low-cost carbon dioxide removal through tropical reforestation,” *Nature Climate Change*, June 2019, Volume 9, Number 6, pp. 463–6.
[22] This includes emissions from living biomass, soils and peatland. The potential from avoiding peatland degradation in temperate regions is not included in this analysis. Based on Bronson W. Griscom et al., “Natural climate solutions,” *PNAS*, October 31, 2017, Volume 114, Number 44, pp. 11645–50, it represents ~10 percent of total peatland avoided degradation potential.
[23] Jens Engelmann and Jonah Busch, “Replication data for potential for low-cost carbon dioxide removal through tropical reforestation,” *Harvard Dataverse*, 2019, V5, dataverse.harvard.edu.
[24] MAC are developed by reducing the potential agricultural revenue (the main driver of forest loss) with a carbon price incentive ($/$tCO_2$), all other variables remaining constant.
[25] According to Busch et al, a carbon price of $20/$tCO_2$ would incentivize land users to reduce deforestation by 2.36 Mha/year, corresponding to 1.83 Gt CO_2/year (55.1 Gt CO_2 and 70.9 Mha over the 2020–2050 period), while a carbon price of $50/$tCO_2$ would reduce deforestation by five Mha/year or 3.61 Gt CO_2/year (149.7 Mha or 108.3 Gt CO_2 over the 2020–2050 period)
[26] Charles S. Hopkinson et al., “Chapter 1 - Coastal Wetlands: A synthesis,” in *Coastal Wetlands, Second Edition: An integrated and ecosystem approach* (Cambridge: Elsevier, 2019), pp. 1–75.
[27] Extent mangrove data were obtained from Global Mangrove Watch (1996–2016) while those of seagrass habitats were obtained from Ocean Health Index Science showing the global distribution of seagrass meadows in 2012 (annual loss rates were obtained from literature review).

which were calculated by comparing a baseline cover to a current cover (the difference allowing to define a restoration potential and to make projections at the 2050 horizon to calculate avoided loss). For avoided loss of coastal ecosystems, we also set a threshold for the maximum avoided loss extent, based on the conservative assumption that 30 percent of the ecosystem surface is or will be protected by 2050 and thus should not be included in the avoided loss extent. The restoration or avoided loss extent was then multiplied by carbon sequestration values.[28]

Contrary to the generic approach outlined above, we used the agricultural rent from cropland only as livestock farming is probably less representative of the feasibility of coastal NCS.

To calculate avoided coastal impact project costs, only costs for mangrove restoration and degradation were investigated (seagrass restoration or avoided degradation projects are less widespread and hence less data is available for them), making the simplifying assumption (in line with expert recommendations) that the cost of restoration was equal to the cost of avoiding degradation plus the cost of planting trees.[29]

Peatland restoration

We combined four main sources to obtain the extent and emission reductions from peatland restoration: (i) a spatial database of the extent of global peatlands (PEATMAP), (ii) a land cover map at 300 meter resolution,[30] (iii) a country database of the extent of degrading peatland in 1990 and 2008,[31] and (iv) emissions factors.

Following Leifeld and Menichetti (2018), we first overlaid the peatland area with the land cover map. When covered by cropland, the peat area was considered to be degraded. We then summed the degrading area by country and compared it with the degrading extent reported in the country database for 2008. In case the calculated extent was higher than the one reported in the database, we considered the calculated extent to be the more accurate. In the other case, we distributed the remaining degraded extent over all other non-degrading areas of the peatland map, proportionally to its area.

We then multiplied the degraded areas by their respective emission factors, depending on their biome and land cover.[32]

We considered the total area for restoration to be equal to the current degrading area (51 Mha).

We used our standard cost methodology to calculate peatland restoration project costs.[33]

Trees in cropland

We used the results of Chapman et al. (2020) to estimate the potential that can be achieved by adding trees to crop systems. First, they estimated current carbon stocks in cropland based on a global map of above- and below-ground biomass. Furthermore, using a threshold of five tCO_2 per hectare (ha) to distinguish croplands lacking woody biomass (less than or equal to five tCO_2 per ha) from those containing woody biomass (greater than five tCO_2 per ha), they calculated the median carbon stocks in the latter category for

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[28] Different carbon sequestration values were used for restoration of the coastal ecosystem versus the avoided loss of the coastal ecosystem. For mangroves, we applied a constant carbon sequestration rate of 6.4 tCO_2 per hectare per year (Griscom, 2020) across the globe for restoration and of 11.7 tCO_2 per hectare per year for avoided loss. For seagrasses, we applied a constant carbon storage value of 3.4 tCO_2 per hectare per year for seagrass restoration (Griscom et al., 2017) across the globe and 4.7 tCO_2 per hectare per year for the avoided loss of seagrass meadows (Pendelton et al., 2012).

[29] Land costs provided by experts for avoided coastal impact sometimes differs from those used for reforestation/avoided deforestation projects.

[30] ESA CCI-LC

[31] Hans Joosten, *The global peatland CO2 picture: Peatland status and drainage related emissions in all countries of the world*, Ede, NL: Greifswald University & Wetlands International, 2009.

[32] See table 1 from Jens Leifeld and Lorenzo Menichetti, "The underappreciated potential of peatlands in global climate change mitigation strategies," *Nature Communications*, March 14, 2018, Volume 9, Article Number 1071, nature.com.

[33] Land costs provided by experts for peatland restoration sometimes differs from those used for reforestation/avoided deforestation projects.

each land unit (biome or country) and assigned this value as the sequestration potential that can be achieved by planting trees in cropland in a given unit. Finally, they multiplied the cropland area with the sequestration rate, assuming an adoption rate between 1 and 10 percent. We retained the scenario of a 5 percent adoption rate (i.e., 5 percent of cropland area currently below five tCO_2 per ha is planted with trees).

To calculate trees in cropland project costs, we assumed similar costs structures as for reforestation, with two main differences: (i) site-set-up costs (especially the planting of trees) were factored down as planting density will be much lower and (ii) recurring maintenance costs were also considered as lower as these tasks cannot easily be differentiated from other cropland maintenance tasks carried out by the main land-user. Land costs were not included since the implementation of this NCS has no opportunity cost given full overlap with cropland.

Cover crops

To estimate the theoretical extent of cover crops, we started from a global cropland area of 1571 Mha (FAOSTAT, 2018) from which we removed cropland already planted with a perennial or winter crop (Poeplau and Don, 2014; Griscom et al., 2017) or where climatic factors and cropping systems require a fallow period. To do this at the granular level, we first computed the Crop Duration ratio (CD), representing the percentage of the year a field is cropped. Following Sieberth et al. (2010), CD was calculated at a minimum degree five-pixel resolution as the mean growing area[34] divided by the cropland extent.[35] Conservatively, we considered that areas with CD less than or equal to 60 percent (corresponding to about five months of off-season) to be suitable for cover cropping. We further filtered out areas under high water stress.[36] Finally, we computed the percentage of cropland suitable for cover crop per country and applied this number to the current cropland area[37] to estimate the total current cropland area suitable for cover cropping.

In most countries, we assumed an adoption rate of 50 percent by 2050 (Poeplau and Don, 2014), but based on expert insights we adjusted this to 60 percent or 80 percent in some geographies. We also excluded 3 percent of the remaining surface to accommodate the surface area required to produce the necessary seeds (Runck et al., 2020), as well as croplands on which cover crops are already being used. We applied a carbon sequestration rate of 1.17 tCO_2 per ha per year based on a recent global meta-analysis on the impact of cover crops on soil organic carbon (Popleau and Don, 2015).

Our cost calculations for cover crop differ from those of other NCSs as we included an estimate of the direct economic benefits accruing to farm operators of using cover crops. As such, we present both gross and net costs of CO_2 with cover crops. Key cost components are: (i) seeds, (ii) planting, and (iii) terminating the cover crops, which recur every year. We include three types of economic benefits: (i) reduced input costs, starting in the second year after adopting cover crops, (ii) increased revenue from higher yield of the main crop (starting in year three) and, in some countries, (iii) revenue from the sale of the cover crop harvest (starting in year one). Land costs were not included since the implementation of this NCS has no opportunity cost. Contrary to other NCSs, we assume annual carbon certification costs to be fixed per project and equal across countries.

[34] Average of the 12 monthly growing areas per grid cell. Data from Felix T. Portmann, Stefan Siebert, and Petra Döll, "MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling," *Global Biochemical Cycles*, March 2010, Volume 24, Number 1, agupubs.onlinelibrary.wiley.com.

[35] Navin Ramankutty et al., "Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000," March 2008, Volume 22, Number 1, agupubs.onlinelibrary.wiley.com.

[36] We exclude areas where water stress is projected to be extremely high (greater than 80 percent) or to be arid in 2040, based on scenario RCP 8.5 (WRI Aqueduct)

[37] FAOSTAT, Land Use 2018

Co-benefits results table

● High
● Medium
● Low

Natural climate solution	Benefit	Benefit level	Rationale
Avoided deforestation	Sequester carbon	●	High benefits of avoided carbon emission and continued carbon sequestration. Benefits will be especially high in humid tropical forests, in high-biomass temperate forests of western North America, and within large, temperate, forested regions of eastern North America, central Europe, and Asia, and in southern and eastern Asia.
Avoided deforestation	Safeguard biodiversity	●	High and immediate biodiversity benefits by maintaining intact and connected forests. Benefits will be very high in humid and semi-arid tropical forests that have high biodiversity. Benefits will also be disproportionately high in forest regions that have high numbers of endemic species and in forest regions that have experienced high proportions of forest loss. Avoided deforestation generally will have high benefits for biodiversity across all biomes compared with the land uses that would replace forests. And avoided deforestation has high local and regional biodiversity benefits within all biomes when it preserves forest in agricultural or urban regions with sparse remaining forest area. Benefits of temperature reductions by forests in tropical and temperate regions in both terrestrial and aquatic habitats that will benefit organisms that are sensitive to air temperature fluctuations or that require lower water temperatures.
Avoided deforestation	Soil health	●	Benefit of prevention of erosion by physical buffering of high stream flows and by prevention of flash flooding by existing forest. Benefit of maintenance of soil infiltration by vegetation and soil fauna under forest. Benefits will occur under a wide range of forest types across biomes and across wet to dry regions. Benefits likely to increase in the future with a predicted greater number and magnitude of extreme precipitation events.

- ● High
- ● Medium
- ● Low

Natural climate solution	Benefit	Benefit level	Rationale
Avoided deforestation	Water quality	High	High benefit of nutrient uptake and retention of nitrogen and phosphorus by forest vegetation that prevents nutrient losses to watersheds that would occur during forest clearing or under alternative agricultural land uses. Benefits will occur across a wide range of forest types. Benefits will be greater in locations where forest conversion would create intensively-managed and heavily-fertilized croplands compared with continuously-vegetated and more nutrient-retentive grazing lands.
Avoided deforestation	Water supply	Low	Benefits of regulation of stream and river water flows within watersheds, reduced water losses during high flow periods, and maintenance of more evenly distributed and more easily captured stream flows. Potential benefits at large regional to continental scales from forest evapotranspiration of water that sustains precipitation at large scales, although the magnitude and distribution of these effects is less certain. Maintaining forest in watersheds also reduces total water yield to aquifers and streams compared with yield in the absence of forest. These effects of forest are larger in tropical than temperate regions but many also occur in humid regions in areas with adequate water supplies. Forest cover could have negative effects particularly in dry locations where forest has expanded onto previously non-forested lands and where water yields to streams and rivers are limited.
Reforestation	Sequester carbon	High	High potential to sequester carbon in regrowing natural forests. Potential for both short and long-term carbon sequestration is highest in humid tropical and temperate regions with high rates of tree growth and high-biomass forests. Land areas available for reforestation are highest in countries with large current amounts of grazing land created from former forest, including Brazil, China and India. Benefits of reforestation generally will be greatest in the forest regions where benefits of avoided deforestation also occur. Reforestation success will be more predictable in temperature regions where

- High
- Medium
- Low

Natural climate solution	Benefit	Benefit level	Rationale
			the availability of native trees for replanting is high and where replanting after forest harvest is a well-established practice. Reforestation success will be more uncertain in tropical regions where forests are more diverse, availability of native trees for planting is lower, and barriers to tree establishment such as drought and damage by grazing are larger.
Reforestation	Safeguard biodiversity	Medium	High ultimate potential to protect biodiversity rapidly in replanted secondary forests but full benefits to biodiversity require many decades to be realized as forests mature. Benefits will be highest for reforestation that expands or reconnects existing remaining forest, in forest regions that have high numbers of endemic species, and that have experienced high proportions of forest loss. Benefits will be greater for reforestation of riparian forests because of the positive effect on both terrestrial and aquatic species, and because of the potential to reconnect forest corridors along stream networks. Benefits will be greater for reforestation with native tree species as compared with non-native tree species. Because regrowing forests increase in stature and complexity over time, benefits to biodiversity of reforestation will take time to accrue, as compared with avoided deforestation. Benefits to biodiversity will occur over one to several decades in less diverse boreal and temperate forests, but will accrue over longer periods of many decades in diverse tropical forests.
Reforestation	Soil health	Medium	Benefit of reduced soil compaction, increased water infiltration and accelerated cycling of soil nutrients that occur with reforestation and associated return of inputs of leaf litter. Associated benefit of reduced soil loss to erosion follows from reduced compaction and greater infiltration. Benefits will occur widely across biomes and forest types. Benefits will be greatest in areas with soils that were severely degraded by overgrazing.

- High
- Medium
- Low

Natural climate solution	Benefit	Benefit level	Rationale
Reforestation	Water quality	High	High benefits to water quality from reforestation by reductions in erosion and soil loss caused by lower compaction, greater infiltration, and more buffered peaks of stream flows in replanted forests. High benefits of reduced movements of soil and soil-associated phosphorus to streams and lakes. Benefit of reduced nitrogen runoff because of increased nitrogen uptake in regrowing forests. High potential to improve water quality on former grazing lands by eliminating direct contact of grazing animals with streams and lakes. Reforestation of riparian forests along streams and rivers will increase nutrient interception and will provide greater benefits to water quality than reforestation of equivalent areas far from stream. Benefits to water quality from reduction of phosphorus movement will occur mostly in freshwater streams and lakes. Benefits to water quality from reduction of nitrogen movement will occur primarily in saline coastal bays and near-shore coastal zones. Highest benefits from phosphorus retention from reforestation will occur on lands mapped as highly susceptible to erosion including in much of eastern North America, eastern China, central and southern Europe, and intensive croplands of South America. Highest benefits to water quality from nitrogen retention will occur on lands near but downstream of intensive and heavily-fertilized agriculture where reforested lands can intercept runoff from croplands.
Reforestation	Water supply	Low	Benefits of reforestation for water supply will be similar to those resulting from avoided deforestation and include regulation of stream and river water flows within watersheds, reduced water losses during high flow periods, and maintenance of more evenly distributed and more easily captured stream flows. Reforestation will reduces land temperatures in tropical and temperate forests and evapotranspiration by regrowing forests will provide moisture that maintains rainfall at large scales, although the magnitude and locations of these benefits remain uncertain. Reforestation will reduce

- High
- Medium
- Low

Natural climate solution	**Benefit**	**Benefit level**	**Rationale**
			total watershed water yields by increasing evapotranspiration through regrowing trees. Effects of reforestation on water yields will be larger in humid tropical regions that often have adequate annual precipitation and water supplies. Reforestation could have negative effects of reducing stream flows in dry regions at the margins of climates that can sustain forest and where water supplies are limited.
Avoided wetland and peatland impacts	Sequester carbon	High	High benefits of avoided carbon emission and continued carbon sequestration in trees and soil especially in tropical peat forests and in temperate and boreal wetland forests with high soil carbon that would be released upon forest loss and soil drainage. High potential for continued carbon capture and burial in river floodplain and delta wetlands.
Avoided wetland and peatland impacts	Safeguard biodiversity	High	High overall biodiversity value for existing wetlands across all biomes. Particularly high biodiversity benefits in tropical peat forests especially in Southeast Asia. High biodiversity benefits in connected wetland lowland forests. Lower biodiversity benefits in higher latitude temperate and boreal wetlands that have lower overall plant and animal biodiversity.
Avoided wetland and peatland impacts	Soil health	High	High benefits from avoidance of losses of soil organic matter that accompany soil drainage. Benefit of avoidance of acid conditions that follow drainage of some peat wetland soils.
Avoided wetland and peatland impacts	Water quality	High	High benefits from avoidance of large nutrient losses that accompany forest removal. Avoidance of acid drainage water or high nutrient releases that accompany drainage of some peat soils. Maintenance of significant nutrient retention capacity in wetlands. Nutrient removal benefits will be greater for riparian, riverine and delta wetlands and particularly high for wetlands that lie in landscape positions that can intercept water draining from croplands.

● High
● Medium
● Low

Natural climate solution	Benefit	Benefit level	Rationale
Avoided wetland and peatland impacts	Water supply	Low	Changes to water supply will be relatively small because of existing adequate water supplies in water-rich wetlands.
Avoided grassland conversion	Sequester carbon	Medium	Potential to maintain current rates of soil carbon sequestration and avoid carbon losses associated with conversion of native grasslands to croplands. Area of potential grassland conversion is small in North America, China and Europe but much larger in South America and Africa.
Avoided grassland conversion	Safeguard biodiversity	High	High potential to protect biodiversity by conservation of existing grasslands. Benefits are largest in temperate regions over which original grassland areas have been severely reduced. Large benefits in South American and African grasslands and savannas with very high biodiversity.
Avoided grassland conversion	Soil health	High	High potential to protect soil structure, organic matter stocks, and water infiltration of native grassland soils. Area of potential conversion is limited in northern hemisphere but large in South America and Africa.
Avoided grassland conversion	Water quality	High	High potential to sustain capture of nitrogen and phosphorus in native grassland soils and avoid water quality impacts that occur after conversion to cropland.
Avoided grassland conversion	Water supply	Low	Little effect on water supply of replacing grassland with grazing land or croplands that have similar vegetation structure and thus similar evapotranspiration rates.
Natural forest management	Sequester carbon	Medium	Modest potential to alter carbon storage in existing natural forests by management that increases forest growth or alters species composition to favor trees with dense wood. Potential to increase carbon stocks by lengthening time to forest harvest. Very large potential area of existing natural forests, but hard to implement, and small changes in carbon

High
Medium
Low

Natural climate solution	Benefit	Benefit level	Rationale
			storage from most management changes will be hard to measure.
Natural forest management	Safeguard biodiversity	Medium	Modest potential to alter biodiversity by management within existing natural forests because most biodiversity benefits are already relatively high in existing forests. Some potential to avoid damage caused by logging practices. These will vary greatly across locations and these effects will be less in places where there is broad compliance with logging best practices but higher in locations were compliance is less and damage to forests by logging is greater. Modest potential to manage for target species or groups of target species depending location. Some forest biodiversity management involves forest thinning or prescribed fire that will reduce forest carbon stocks.
Natural forest management	Safeguard biodiversity	Low	Low potential to alter soil conditions because land is already maintained in forest. Some potential to reduce damage to soil caused by compaction from road construction and logging.
Natural forest management	Water quality	Medium	Modest potential to alter water quality by management because land remains forested and existing water quality benefits are already high in existing forests. Some potential to reduce impacts to surface waters by improved logging practices that reduce erosion, sedimentation and runoff. Potential for improvements will be greatest in locations that have lower compliance with logging best practices.
Natural forest management	Water supply	Low	Little effect on water supply because lands maintained as forests that will have similar rates of evapotranspiration and water cycling.

● High
● Medium
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Natural climate solution	Benefit	Benefit level	Rationale
Wetland and peatland restoration	Sequester carbon	Medium	Carbon sequestration is variable and will depend on wetland type and local setting. The climate mitigation potential of restored wetlands will depend on the degree to which restored wetlands emit methane in quantities that offset potential gains in carbon in soils and vegetation, which is not well known and will also depend on wetland type and local setting. The balances between methane emissions and carbon storage may mean relatively small net greenhouse gas benefits over the first several decades after restoration. In general, potential for carbon storage in vegetation will be higher in forest wetlands with fast-growing trees and lower in marshes with herbaceous vegetation. Ultimate soil carbon sequestration is higher in peat-forming wetlands but rates of carbon sequestration in peat soils is general modest. Methodologies for wetland restoration are well developed for some wetland types such as inland marshes on mineral soils but less developed and less certain for others such as tropical forested peatlands.
Wetland and peatland restoration	Safeguard biodiversity	High	Wetland restoration has generally high co-benefits for biodiversity because of the disproportionately high value of wetland habitats. These values occur across biomes.
Wetland and peatland restoration	Soil health	Medium	Wetland restoration will generally have the co-benefit of returning soils to wetland conditions that have high organic matter input and permanent or periodic low oxygen. While these conditions are not desired in agricultural soils, in wetlands they facilitate carbon storage and the co-benefit of nutrient removal.
Wetland and peatland restoration	Water quality	High	Wetland restoration has high potential co-benefits of improved water quality especially in cropland regions and if wetland restoration occurs in locations that are downstream of fertilized croplands or in locations that have contact with nutrient-enriched surface or ground waters.

● High
● Medium
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Natural climate solution	Benefit	Benefit level	Rationale
Wetland and peatland restoration	Water supply	Low	Wetland restoration may have some co-benefits for water supplies by stabilizing stream and river flows but overall effects on total water yields will be small.
Cropland nutrient management	Sequester carbon	Medium	In cropland regions with high fertilizer use and low gaps between actual and potential crop yields, substantial climate benefits will come from reductions in nitrous oxide emissions that follow from lower fertilizer use and better matching of the timing fertilizer applications with plant nutrient demands. In cropland regions with low fertilizer use and high gaps between actual and potential crop yields, substantial climate benefits will come from increases in crop organic matter production and soil carbon storage that follow from higher fertilizer applications that increase crop yields.
Cropland nutrient management	Safeguard biodiversity	Medium	Little effect on terrestrial biodiversity because land use is not altered. Substantial off-site co-benefits to biodiversity within aquatic ecosystems that lie downstream of croplands that receive better nutrient management that reduces nutrient runoff. The magnitude and location of biodiversity co-benefits will depend on the receiving waters and the nutrient managed. Nitrogen management will have greatest benefits in coastal waters often far from the location of cropland nutrient management. Phosphorus management will have greatest benefits in fresh water rivers and lakes. Benefits will vary according to soil type, existing fertilizer use and current water quality status of receiving waters. Benefits may take a long time to occur because of legacies of high nutrients stored within soils and sediments. Because benefits occur off site, in some watersheds they will be very difficult to trace to a particular management action in croplands.
Cropland nutrient management	Healthy soils	Medium	Potential significant benefits of cropland nutrient management to soil organic matter, structure, infiltration and water holding capacity in locations with low crop yields and high gaps between actual

● High
● Medium
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Natural climate solution	Benefit	Benefit level	Rationale
			and potential yields where increased fertilizer use will increase crop and organic matter production. Effects of better cropland nutrient management will be less in locations with high fertilizer use and low yield gaps.
Cropland nutrient management	Water quality	High	High co-benefits from reductions in the runoff of nutrients from croplands to groundwater and surface waters. Benefits will be large in regions of intensive cropping and high fertilizer use, including in the Mississippi and Ohio River basins and their major tributaries in North America, in central and eastern China, and in Europe. Benefits will also occur in regions with high yield gaps where erosion can be reduced by improvements to soil properties that follow improved nutrient management and crop production.
Cropland nutrient management	Water supply	Low	Little effect on water supply because plant cover and rates of evapotranspiration that control the water cycle are not changed.
Plantation management	Sequester carbon	Medium	Potential for increased carbon storage in plantations arises largely from extending rotation lengths, and the overall potential is lower than for avoided deforestation or reforestation. While the potential to increase carbon sequestration on a per area basis, the total area of forest plantations is small compared with the area of natural forests. Greater productivity on plantation forests could lower demand for natural forest harvest. Future opportunities may exist through selective breeding or genetic modification to increase growth rates and to increase the longevity of wood products. Benefits will be larger in humid and tropical and warm regions with rapid tree growth.
Plantation management	Safeguard biodiversity	Low	Relatively low biodiversity co-benefits from changing management within existing plantation forests. Plantation forests have simpler structure and lower overall co-benefits across multiple levels

● High
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Natural climate solution	Benefit	Benefit level	Rationale
			of biodiversity compared with more complex and multi-species natural forests. Management of plantation forests for higher productivity has potential biodiversity benefits of reduced harvest from natural forests.
Plantation management	Soil health	Low	Relatively low co-benefits to soil health from changing planation management because land is already forested. Some potential benefits if longer harvest rotations reduce soil disturbance and compaction.
Plantation management	Water quality	Low	Relatively low additional water quality co-benefits caused by change in management of existing forests that already provide substantial water quality co-benefits. Water quality co-benefits of improved logging practices might be slightly greater than in natural forests because logging occurs more frequently but that might be balanced by potentially greater existing compliance with best management practices in plantation compared with natural forests.
Plantation management	Water supply	Low	Changes to management within existing plantation forests would have little effect on forest structure and would therefore have little effect on rates of evapotranspiration or infiltration that would influence water supply.
Trees in cropland	Sequester carbon	Medium	Modest potential to increase carbon stored in trees within existing croplands. Potential is generally less than one-third of the potential of avoided deforestation or reforestation. Benefits will be widespread across biomes but greatest in humid and warm regions with rapid tree growth. Modest benefits to soil carbon by erosion reduction. There are constraints on potential for tree planting within croplands because of direct competition with crops for space and light. Constraints on increases in planted or spontaneous tree cover within grazing lands may be less. Measurement of tree cover within

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Natural climate solution	Benefit	Benefit level	Rationale
			agricultural lands is difficult because the difficulty of detection of individual trees within croplands by remote sensing.
Trees in cropland	Safeguard biodiversity	Medium	Modest potential for co-benefits to biodiversity by addition of structural complexity to croplands. Co-benefits will occur across all biomes but will be greater in tropical regions with high biodiversity and in regions that have low proportions of remaining forest area. Biodiversity co-benefits will increase with the number and density of trees.
Trees in cropland	Soil health	Low	Relatively low co-benefits to soil health from adding scattered trees to croplands. Some potential for reduced erosion. Benefits will increase with the number and cover of trees and will vary by location. Benefits will be higher if trees are planted as buffer between croplands, streams, rivers and lakes.
Trees in cropland	Water quality	Low	Relatively low co-benefits to water quality from adding scattered trees to croplands. Benefits will be higher if trees are planted within heavily-fertilized croplands and if they are concentrated along streams or watercourses where they could intercept nutrient runoff.
Trees in cropland	Water supply	Low	Relatively little effect of adding trees to croplands because if overall change to tree cover is small. Water supply effects will be larger with increases in the number and cover of trees. Some potential negative effects of trees in drier regions if they compete with crops for water.
Conservation agriculture—cover crops	Sequester carbon	Medium	Modest potential to store soil carbon by planting of perennial crops during periods when main crops are not growing. But potential is limited by the short duration of cover crops in most planting systems and potential conflicts with crop production if cover crops remain for longer periods like during entire crop growing seasons. Large potential new area over which cover crops could be planted. Indications

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Natural climate solution	Benefit	Benefit level	Rationale
			that much new stored soil carbon could be lost relatively quickly if cover cropping is discontinued.
Conservation agriculture—cover crops	Safeguard biodiversity	Low	Low to modest co-benefit to biodiversity compared with reforestation because land remains cropland with relatively low biodiversity. Some benefits for pollinators for some cover crops but timing of presence of cover during shoulders of growing season may restrict benefits and in general co-benefits to pollinators are not well known and location-specific.
Conservation agriculture—cover crops	Soil health	Medium	Modest co-benefits to soil health from increased organic matter inputs, increased water infiltration, increased water holding capacity and benefits to nutrient supply provided by decay of cover crop-derived soil organic matter.
Conservation agriculture—cover crops	Water quality	Medium	Some potential to reduce nutrient losses by maintaining plant cover for longer time during the year. The deep rooting of many preferred cover crops helps prevent nutrient losses. Short duration of cover crop limits total nutrient capture potential. Benefits will occur across biomes but implementation may be easier in locations with longer growing seasons. Cover crop water quality co-benefits will be larger in locations with high potential for nutrient losses or in watersheds with nutrient-sensitive receiving waters.
Conservation agriculture—cover crops	Water supply	Low	Relatively little effect on water supply because cover crops are present for relatively short periods and not generally during the warmest portions of growing seasons when effects on evapotranspiration and water balance would be greater.

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Natural climate solution	Benefit	Benefit level	Rationale
Conservation agriculture—no-till	Carbon sequestration	Low	Increases in soil carbon storage after conversion to no-tillage are relatively modest. Gains in soil carbon are concentrated near the soil surface. Gains in soil carbon under no-tillage often quickly lost if no-tillage is not continued. Large potential to increase no-till practices on farmlands in many locations but potential limited in some locations, such as corn-cropping regions of North America or soybean-cropping regions in South America because adoption of no-till is already fairly high. Barriers to adoption high in many places because of high equipment costs.
Conservation agriculture—no-till	Safeguard biodiversity	Low	Very little co-benefit for biodiversity from conversion to no-tillage because land remains in intensive cropping.
Conservation agriculture—no-till	Soil health	Medium	Modest co-benefits of increased organic matter at the soil surface, maintenance of crop residues, greater water infiltration. Benefits will occur widely across global cropping regions. Some potential small decreases in soil health because of increased soil waterlogging in some years in wet locations.
Conservation agriculture—no-till	Water quality	Medium	Modest co-benefits to water quality from decreased wind and water erosion caused by greater soil infiltrability and maintenance of crop residues. Little difference in nutrient runoff by conversion to no-tillage.
Conservation agriculture—no-till	Water supply	Low	Very little effect on water supply because no-till does not change the timing or nature of cropping.
Biochar	Sequester carbon	Medium	Co-benefit of increased soil carbon storage when long-lived carbon in the form of biochar is added to soils. Carbon sequestration benefits highly dependent on how biochar produced and the life-cycle energy analysis of biochar sources and production methods. Biochar benefits occur across

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Medium
Low

Natural climate solution	Benefit	Benefit level	Rationale
			biomes. Use of biochar that results in increased forest harvest would have negative carbon consequences.
Biochar	Safeguard biodiversity	Low	Biochar additions to croplands would not change land use and would have relatively little effect on biodiversity. Some modest biodiversity co-benefit of increased diversity of soil micro and macroorganisms with biochar additions.
Biochar	Soil health	Medium	Biochar increases soil pH and can increase soil cation exchange capacity and the ability of soils to retain calcium and other cations that are important plant nutrients in soils. Some potential detriment if biochar production reduces volume of crop residues returned to soil. Biochar can lower soil density, increase soil porosity and increase rates of water infiltration. Biochar can increase crop yields and increases are greater in tropical than temperate croplands. There are challenges applying properly-sourced biochar to large areas.
Biochar	Water quality	Low	Potential co-benefits of increasing the stability of soil aggregates and lowering soil erosion. Overall changes to nutrient runoff are small.
Biochar	Water supply	Low	Few potential changes to water supply because land remains cropland with similar water balance.
Fire management	Sequester carbon	Low	Overall, fire management in global savannas is estimated to provide only a small fraction of the climate mitigation potential of avoided deforestation, reforestation or forest management. High uncertainty in the accounting for carbon that might be retained in forests by prescribed burning that releases carbon in the short term but might retain forest carbon if prescribed burning reduces larger fires at a later date. Very large uncertainties in prediction and ascribing of carbon sequestration to particular locations.

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Medium
Low

Natural climate solution	Benefit	Benefit level	Rationale
Fire management	Safeguard biodiversity	Medium	Fire suppression will have biodiversity co-benefits if implemented in forests that have not evolved with fire especially evergreen tropical forests that now dry sufficiently to burn. Fire management by prescribed burning can have high biodiversity co-benefits in forests that have evolved with regular fires particularly after periods of prolonged fire suppression.
Fire management	Soil health	Low	Potential co-benefits to soil health if prescribed fire or fire suppression can prevent large fires that consume soil organic matter and reduce soil infiltrability. Capacity to predict where these co-benefits would occur is low.
Fire management	Water quality	Medium	Potential modest co-benefits to soil health if prescribed fire or fire suppression can prevent large fires that consume soil organic matter and reduce soil infiltrability. Capacity to predict where these co-benefits would occur is low.
Fire management	Water supply	Low	Potential co-benefit of stabilization of stream flows derived from maintenance of forest cover from prevention of large fires that result in tree mortality. Potential small co-benefit of increased water supply by partial reductions of tree or understory cover by prescribed burning.
Grazing management	Sequester carbon	Low	Grazing management can vary widely and there are potentially very large ranges of carbon sequestration responses and time scale of responses to grazing management. Carbon sequestration is larger in wetter regions where forage growth rate is high and land areas over which management can be applied are smaller and cost barriers to management with fences or other strategies are lower. In drier regions the potential global areas of grazing land are very large but the magnitude of carbon storage is lower.

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Natural climate solution	Benefit	Benefit level	Rationale
Grazing management	Safeguard biodiversity	Low	Generally small co-benefits for biodiversity because land retained as grazing land. Some potential benefits from lowering animal densities or animal rotation management that increases of grass cover especially on degraded lands. Some benefits to aquatic systems from fencing animals from surface waters.
Grazing management	Soil health	Low	Potentially small co-benefits of higher soil organic matter, higher infiltration and lower compaction by animal management.
Grazing management	Water quality	Low	Potentially small co-benefits from reduced animal densities, reduced soil compaction, and reduced direct animal contact with streams, ponds and other water supplies.
Grazing management	Water supply	Low	Little change to water supply or co-benefit because land use remains grazing land.

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