Supporting Information:

Novel Technologies for Emission Reduction Complement Conservation Agriculture To Achieve Negative Emissions From Row Crop Production

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The targets for emission abatement are guided by lifecycle analysis (LCA) of grain production from the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model and its derivative Feedstock Carbon Intensity Calculator (FD-CIC) developed at Argonne National Laboratory. Both inventory models are available at greet.es.anl.gov (1, 2). The GREET model incorporates agricultural feedstock modules to account for the emission footprint of grain production for biofuels. Inventory estimates in GREET rely on primary literature and publicly available datasets. For agricultural feedstock GHG inventories, GREET uses data from USDA and primary literature that represent modern management practices including fertilizer and chemical application and yield.

The LCA results of GREET have important policy implications because they are used to determine carbon credit values for biofuels by California Air Resources Board for its Low Carbon Fuel Standard (LCFS), by the U.S. Environmental Protection Agency for the Renewable Fuel Standard, by the Oregon Department of Quality for its Clean Fuel Program, by Environment and Climate Change Canada for its forthcoming Clean Fuel Standard, and by International Civil Aviation Organization for its Carbon Offsetting and Reduction Scheme for International Civil Aviation (CORSIA). While primarily motivated by these programs, GREET is broadly applicable to grain production and has been used to estimate the carbon footprint of large grain buying companies (3) and for animal production systems (4).

Nitrous oxide (N_2O) is the largest segment of GHG emissions from row crop agriculture due to its global warming potential (265x CO_2). N_2O is generated when N fertilizer undergoes nitrification and denitrification processes in the soil and from decay of crop residues left in the field. The remaining emissions are Carbon Dioxide (CO_2), and the largest source is CO_2 generated by the production of ammonia by Haber Bosch for fertilizer. The remaining emissions come from fuel consumption for farm equipment and chemical manufacture such as lime, other nutrients, herbicides, and insecticides.

The default values reported here are the weighted national average emission baseline for corn production, which are used to calculate the carbon impact of corn production in the US. These values are instructive for impact assessment of practice change or technical innovation (5). For this paper, GREET2020 and FD-CIC2020, as released in Oct. 2020, were used.

Table S1 includes the values used to generate Figure 1, starting with GHG emission values based on US corn production, separated by emission source. The subsequent rows contain the value for each of these sources with an expected reduction from the default value based on the emission reduction potential of a new technology. Although this benchmark is for corn, these innovations apply to wheat, sorghum, soybean, cotton, etc. and could reach more than 80M hectares in the U.S.

These values are single average values that reflect the potential of emission reduction of the technologies. Although any given field will vary, these values are useful for an aggregate estimate of the magnitude of emission progress from technology deployment. The dates given reflect when the technology could be adopted, and actual adoption must follow. Scaling emission reduction will take time, however if incentives are designed correctly, many of the technologies can follow rapid adoption curves as has been seen for other agricultural technologies.

The Phases are marked by the technical readiness of enabling technologies:

- Optimize (Phase 1) – near-mature technologies that will become economically viable with policy or value model changes (e.g. emission credits) and information to address social barriers.
- Replace (Phase 2) – Most of the technologies described in this section are prototypes that are scalable and will be prioritized for development to production level when they become economically viable after policy or value model change.
- Redesign (Phase 3) – These technologies are conceptual and will be prioritized from early-stage research based on the new optimization for low emission agriculture. Most of the technologies will require significant development (5-15 years) and furthermore imply significantly different practices. Education and support need to be developed in tandem so that as these technologies emerge from the research pipeline producers are equipped to use them effectively.

Table S1. Baseline GHG Emissions and Emission Reduction Potentials of Technology Deployment: Units are expressed as kg CO_2e/ha of corn production and g CO_2e/MJ of corn ethanol (the latter is presented in parathesis)[1]

Emission Source	Current Default	Optimize	Replace	Redesign
N2O from Biomass Decay in field	296 (3.1)	296 (3.1)	296 (3.1)	148 (1.6)
N2O from Fertilizer Loss in field	866 (9.1)	554 (5.8)	554 (5.8)	277 (2.9)
Nitrogen Fertilizer Manufacture	506 (5.3)	324 (3.4)	162 (1.7)	32 (0.3)
Fuels/Energy	261 (2.7)	261 (2.7)	91 (1.0)	26 (0.3)
P/K Fertilizers and Chemicals	187 (2.0)	187 (2.0)	93 (1.0)	93 (1.0)
Urea Manufacture	233 (2.4)	149 (1.6)	149 (1.6)	58 (0.6)
Lime and CO2 in field	120 (1.3)	120 (1.3)	120 (1.3)	90 (0.9)
Total[2]	2469 (26.0)	1891 (19.9)	1466 (15.4)	725 (7.6)
% reduction		23%	41%	71%
Absolute Reduction		578 (6.1)	1003 (10.5)	1744 (18.3)

[1] GHG emissions in the FD-CIC model are presented in g CO_2e/bushel of corn harvested. To convert that to kg CO_2e/ha, the model uses a corn yield of 166 bushel per acre (410 bushels per hectare). The table includes GHG emissions per MJ of corn ethanol because this unit is used by the California Low Carbon Fuel Standard and the EPA Renewable Fuel Standard to determine

the GHG intensities per MJ of fuel delivered. To calculate values in g/MJ, the FD-CIC model uses an ethanol yield of 2.88 gallons per bushel of corn, the current average ethanol yield of U.S. dry mill ethanol plants. This value is converted to energy content using the lower-heating value of ethanol of 80.52 MJ/gallon.

[2] Totals are slightly different due to independent rounding.

The reductions detailed below are based on technical solutions described in the paper:

- Biomass decay – These emissions occur through the release of N_2O from decaying biomass and converted to CO_2e with the global warming potential of 265x CO_2.
    - Phase 1 – Unmodified
    - Phase 2 – Unmodified
    - Phase 3 – projected 50% reduction in N_2O released from decaying biomass through biotechnology / genetic modification that leads to relocalization of nitrogen to the root zone where it can be used by future crops rather than lost as N_2O
- Fertilizer loss – These are the emissions associated with unused fertilizer that is converted to N_2O with an emission factor of 1.35% determined by the UN from meta-analysis (6) and converted to CO_2e with the global warming potential of 265x CO_2.
    - Phase 1 – 36% reduction in applied N can be achieved by digital ag adoption and optimal N use that matches the biological demand (7). The reduction in fertilizer application leads to a reduction in N_2O release.
    - Phase 2 - No additional technical development is expected at this phase, and the emission reduction from the optimize phase is maintained.
    - Phase 3 – A 36% reduction in fertilizer application through digital ag is continued, and an additional 50% reduction in N_2O release is projected by reducing the emission factor through plant breeding, improved N placement by biological amendments, and adoption of stabilized inputs.
- Nitrogen Fertilizer Manufacture – These are CO_2 emissions that are the direct result of energy use in the production of ammonia via Haber Bosch.
    - Phase 1 – 36% reduction reflecting reduced application
    - Phase 2 – 50% reduction in emissions per unit of fertilizer through transition from fossil powered Haber Bosch to renewable ammonia (8), as is currently being achieved at a small number of prototype plants in operation.
    - Phase 3 - 90% reduction in emissions per unit of fertilizer through electrification of ammonia or nitrate synthesis using renewable electricity, air, and water with new technologies (9).
- Fuels / Energy – This emission is largely the result of diesel combustion by farm equipment.
    - Phase 1 – No modification
    - Phase 2 – Projected effect of adoption of electric tractors that reduce emissions by 65% using current average electricity mix. This is the same value assigned by the Department of Energy for electric vehicles replacing internal combustion engines (10)

- Phase 3 – Emissions reductions of 90% from the default value can be achieved by adopting autonomous electric equipment and electric tractors and shifting the blend of electricity generation toward renewables.

- Chemical Application – These are emissions associated with other chemicals beside nitrogen fertilizer including P, K, herbicides, and insecticides.
  - Phase 1 – Unmodified
  - Phase 2 – Similar to nitrogen reduction based on precision agriculture, a 50% reduction is forecasted in chemical and fertilizer through targeted application based on biological demand and pest pressure using surveillance rather than broad acre application (11)
  - Phase 3 – No further reduction is projected, and the 50% reduction is continued based on targeted chemical application.
- Urea Manufacture – These are additional emissions that are incurred when urea is manufactured from ammonia, and the same reductions in application are applied as above. In addition to reduced fertilizer use, a shift to other N sources is projected in the redesign phase.
  - Phase 1 - 36% reduction in phase 1 through digital ag adoption and optimized fertilizer application.
  - Phase 2 - In this phase there is no further reduction in emissions in this category.
  - Phase 3 – In the redesign phase, a 75% reduction in this source of emissions is forecasted based on the application of other nitrogen sources that have a lower emission profile.
- Lime – These emissions are comprised of CO_2 emissions from the production and application of lime.
  - Phase 1 – Unmodified
  - Phase 2 – Unmodified
  - Phase 3 – In phase 3 a 25% reduction in lime application is forecasted based on precision mapping for application and the potential for elite genetics to tolerate broader soil conditions.

Each phase is summed and then compared with the current default values to estimate the potential emission reduction. These values assume the full technical potential of each phase.

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