CHAPTER-26

IS CLIMATE-SMART AGRICULTURE COHERENT IN HIGH-INPUT SYSTEMS? A THREE-PILLAR AUDIT OF UNITED STATES CORN PRODUCTION, 2000 TO 2023

Vallabh Verma[1] & Arshad Bhat[2]
[1]Melbourne Business School, University of Melbourne, Australia
[2]Amity Institute of Liberal Arts, Amity University Mumbai, Maharashtra, India
Corresponding author: valabhv@student.unimlb.edu.au

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Abstract

The climate-smart agriculture (CSA) framework articulated by the Food and Agriculture Organization rests on three pillars: sustainable increases in productivity, improved resilience to climate variability, and reductions in greenhouse gas emissions per unit of output. While CSA has been applied extensively to smallholder systems in the Global South, its application to high-input industrial cropping systems remains theoretically underdeveloped. This paper asks whether the contemporary United States Corn Belt production system, which serves as a global benchmark for cereal productivity, satisfies the CSA framework on its own stated terms. Using a structured framework analysis that synthesizes published empirical findings from agronomic field experiments, econometric productivity studies, and biogeochemical meta-analyses, the paper evaluates United States corn production against each CSA pillar, with particular attention to the role of nitrogen fertilizer as the master input of the industrial corn system. Evidence drawn from the peer-reviewed literature reveals an asymmetric pattern across pillars: strong satisfaction of the productivity pillar, ambiguous or weakening performance on the resilience pillar, and clear failure on the mitigation pillar. The paper argues that applying the climate-smart label to high-input commodity grain production represents a category error and discusses implications for United States climate and agricultural policy.

Keywords: climate-smart agriculture, nitrogen fertilizer, corn production, greenhouse gas emissions, yield variability, United States Corn Belt.

1. Introduction

Few phrases in contemporary agricultural policy carry as much rhetorical weight, and as little analytical discipline, as the term climate-smart agriculture. Since the concept was formalized by the Food and Agriculture Organization at the 2010 Hague Conference, it has become a near-universal descriptor for any agricultural intervention that its proponents wish to associate with environmental virtue (FAO, 2013; Lipper et al., 2014). The foundational definition is nevertheless precise. Lipper et al. (2014) identified three constitutive pillars: sustainably increasing agricultural productivity and incomes, adapting and building resilience of food systems to climate change, and reducing or removing greenhouse gas emissions where possible. A system that is climate-smart, by this definition, must perform acceptably on all three. A system that excels on one while failing the others is, at best, incompletely climate-smart and, at worst, a misuse of the label.

The theoretical appeal of the three-pillar framework is that it provides a common yardstick against which heterogeneous agricultural systems can be compared. Yet the bulk of the CSA literature has been applied to smallholder systems in sub-Saharan Africa, South Asia, and Latin America, where the baseline challenges of low productivity, climate exposure, and limited adaptive capacity make the framework a natural fit (Campbell et al., 2014; FAO, 2013; Lipper et al., 2014). Applications to high-input, mechanized, commodity grain production in the industrialized world are far less common, even though such systems account for a disproportionate share of global agricultural greenhouse gas emissions and nitrogen flows (Robertson & Vitousek, 2009; Smith et al., 2014; Zhang et al., 2015). This asymmetry in the literature reflects a tacit assumption that industrial systems have already solved the productivity problem and that adaptation and mitigation can be addressed incrementally, without questioning the underlying production model.

This paper challenges that assumption by applying the three-pillar framework to the archetype of high-input grain production: the United States Corn Belt. Corn is the largest crop in the United States by planted area, typically occupying between 88 and 95 million acres in recent years (USDA NASS, 2024). Yields have risen from approximately 138 bushels per acre in 2000 to over 177 bushels per acre by 2023, a trajectory frequently cited as evidence of the sector's sustainability credentials (Cassman & Grassini, 2020; Grassini et al., 2013). Yet the same system is the largest domestic consumer of synthetic nitrogen fertilizer, which is the single largest source of direct nitrous oxide emissions from United States soils and a major contributor to downstream water pollution (Cavigelli et al., 2012; EPA, 2024; Robertson et al., 2013). The Corn Belt is therefore an unusually clean test case: a system that plainly satisfies the first pillar, whose performance on the other two is in active scientific dispute.

2. Productivity and the nitrogen-yield relationship

The productivity record of United States corn is without parallel in the global cereal sector. Kucharik and Ramankutty (2005) decomposed twentieth-century Midwest yield growth and attributed roughly equal shares to genetic improvement and agronomic management, with synthetic nitrogen fertilizer emerging as the dominant agronomic lever after the Second World War. Smil (2001) documented how the industrialization of nitrogen fixation through the Haber-Bosch process restructured global agriculture, enabling yield levels previously constrained by biological nitrogen availability. Agronomic research has long established that the yield response to nitrogen is concave: initial pounds of nitrogen produce large yield gains, but marginal gains decline as rates approach the agronomic optimum (Cassman et al., 2002; Sinclair & Rufty, 2012). This concavity is foundational to the analysis that follows. At the global scale, Mueller et al. (2012) and Ray et al. (2013) have shown that yield gaps remain the dominant determinant of aggregate food production potential. Yet the United States corn system is not a yield-gap story; Grassini et al. (2013) demonstrated through segmented regression that United States corn yields have grown approximately linearly rather than plateauing, while Cassman and Grassini (2020) and Lassaletta et al. (2014) argued that further gains will require improvements in nitrogen use efficiency rather than continued rate increases.

3. Resilience and climate variability

The second pillar concerns resilience to climate variability. The evidence on United States corn resilience is mixed and, in important ways, uncomfortable. Schlenker and Roberts (2009) used county-level panel regression to show that United States corn yields are sharply nonlinear in growing-season temperature, with yields increasing up to approximately 29 degrees Celsius and declining steeply thereafter. Lobell et al. (2014) extended this analysis and reported a finding central to the present argument: despite decades of yield progress, the sensitivity of United States corn yields to drought has actually increased, not decreased, with denser plantings and more closed canopies raising average yields but also increasing vulnerability to evaporative stress. Hatfield et al. (2011) projected that climate change will compress the United States corn growing season and expose the crop to more frequent heat stress during pollination. Burke and Emerick (2016) used a long-difference regression on United States county data and found that long-run farmer adaptation has offset only a modest fraction of short-run climate damages. Ortiz-Bobea et al. (2021) concluded, using a cross-country productivity framework, that anthropogenic climate change has already slowed global agricultural productivity growth by roughly 21 percent relative to a no-climate-change counterfactual. If yield gains have come at the cost of greater climate sensitivity, then the resilience pillar of CSA is not a free gift of productivity growth.

4. Mitigation and the nitrogen-emissions relationship

The third pillar is where the conventional story for United States corn is weakest. Agricultural soils are the largest domestic source of nitrous oxide emissions, a greenhouse gas with a 100-year global warming potential of 273 (EPA, 2024; IPCC, 2019). The dominant proximate driver is synthetic nitrogen fertilizer: applied nitrogen that is not taken up by the crop is subject to microbial nitrification and denitrification, a fraction of which is lost to the atmosphere as nitrous oxide (Davidson, 2009; Robertson & Vitousek, 2009). The canonical Intergovernmental Panel on Climate Change emission factor assumes that approximately one percent of applied nitrogen is emitted as direct nitrous oxide (IPCC, 2019). The central finding that motivates this paper, however, is that the relationship between applied nitrogen and emissions is not linear. Hoben et al. (2011), studying on-farm corn in Michigan, found that nitrous oxide emissions rose exponentially with applied nitrogen, with emissions per unit of nitrogen accelerating sharply beyond agronomic optima. Shcherbak et al. (2014), in a global meta-analysis covering 78 published studies, confirmed this nonlinear response and estimated that emission factors at high nitrogen rates can be several times the default linear value. Because corn yields respond to nitrogen with diminishing returns while emissions respond with increasing returns, the emissions intensity of corn, measured as greenhouse gases per bushel produced, is expected to rise with applied nitrogen beyond the efficiency optimum (Reay et al., 2012; Snyder et al., 2009).

5. The three-pillar gap and research question

Despite the richness of these three literatures, no published study known to the author has evaluated contemporary United States corn against all three CSA pillars simultaneously. Most applied CSA studies target smallholder systems (Campbell et al., 2014; Lipper et al., 2014; Paustian et al., 2016), while United States corn studies tend to focus on a single outcome at a time. The absence of a three-pillar audit is consequential because the three pillars can move in opposing directions in response to the same input. If nitrogen simultaneously raises yields, leaves resilience unchanged or weakened, and worsens emissions intensity, then the same management decision that secures the productivity pillar actively undermines the mitigation pillar. Such asymmetry, if confirmed, would render the CSA label incoherent when applied to United States corn without qualification.

The research question of this paper is therefore direct. Does the contemporary United States Corn Belt production system satisfy all three pillars of the climate-smart agriculture framework as those pillars were originally defined? The analytical expectation, drawn from the literature reviewed above, is that the system satisfies the productivity pillar strongly, the resilience pillar weakly or not at all, and the mitigation pillar not at all. The contribution of the paper is twofold. Substantively, it provides the first integrated three-pillar audit of United States corn and argues that the climate-smart label, as currently used in United States policy discourse, obscures rather than clarifies the system's environmental profile. Methodologically, it demonstrates how a framework designed for qualitative comparison of agricultural systems can be made empirically tractable through structured synthesis of published quantitative findings.

6. Methods

Analytical approach

This paper uses a structured framework analysis to evaluate the United States Corn Belt production system against the three-pillar definition of climate-smart agriculture (Lipper et al., 2014; FAO, 2013). The unit of analysis is the contemporary United States corn production system over the 2000 to 2023 period, treated as a coherent agronomic and economic complex rather than as a set of independent farm-level decisions. Structured framework analysis is a recognized methodology in applied policy research and in the broader sustainability assessment literature, in which a normative framework with stated criteria is applied to a specific case in order to render a defensible verdict on whether the case meets those criteria (Paustian et al., 2016; Smith et al., 2014). The contribution lies in the integration of the framework with the empirical evidence, not in the production of new data.

Evidence base

For each of the three CSA pillars, the analysis proceeds in three steps. The first step identifies the operative outcome variable associated with the pillar: yield for productivity, yield stability for resilience, and emissions intensity per unit of output for mitigation. The second step identifies the dominant input or driver acting on that outcome; in the United States corn system, this is overwhelmingly synthetic nitrogen fertilizer for the productivity and mitigation pillars, and climate variability mediated by crop physiology for the resilience pillar (Hoben et al., 2011; Robertson & Vitousek, 2009; Schlenker & Roberts, 2009). The third step synthesizes published quantitative findings from peer-reviewed agronomic, biogeochemical, and econometric studies that have estimated the relationship between input and outcome for each pillar, with priority given to studies using United States data or to global meta-analyses that explicitly include the United States. Where multiple studies report convergent estimates, the analysis adopts the central tendency reported in the most recent peer-reviewed synthesis. Where studies disagree, the disagreement is reported and discussed.

Sources and selection criteria

Studies were selected on three criteria. First, the study must be peer-reviewed or published as part of an official intergovernmental assessment such as those of the Intergovernmental Panel on Climate Change. Second, the study must report quantitative estimates derived from observed data, with regression-based estimates, meta-analytic syntheses, and process-based modeling all considered admissible. Third, the study must be either set in the United States or include the United States as part of a global sample. Federal statistical data on yield, fertilizer use, and emissions are drawn from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS, 2024), the United States Department of Agriculture Economic Research Service (USDA ERS, 2019), and the United States Environmental Protection Agency Inventory of Greenhouse Gas Emissions and Sinks (EPA, 2024).

Limitations of the approach

The principal limitation of structured framework analysis is its dependence on the quality and coverage of the existing empirical literature. Where the literature is contested or thin, the analysis must report that fact rather than resolve it. A secondary limitation is that the framework itself, the three pillars of CSA, is normative rather than descriptive, and reasonable analysts could weight the pillars differently or propose a different framework altogether. The paper accepts both limitations and treats them as features rather than defects, since they make the analytical structure transparent and falsifiable: another analyst working with the same framework and the same literature should reach broadly similar conclusions.

7. Results

Productivity pillar: strong satisfaction

The evidence in favour of the productivity pillar in United States corn is unambiguous. USDA National Agricultural Statistics Service data show that average national yields rose from approximately 138 bushels per acre in 2000 to over 177 bushels per acre by 2023, an increase of roughly 28 percent in 23 years (USDA NASS, 2024). Grassini et al. (2013) used segmented regression on long-run yield series for major cereal crops and found no statistically significant evidence of yield plateauing in United States corn through the early 2010s, in contrast to wheat and rice in several major producing regions. The trend rate of yield growth estimated in long-horizon regressions on United States corn has converged on approximately 1.9 bushels per acre per year over the post-1950 period (Grassini et al., 2013; Kucharik & Ramankutty, 2005). Cassman et al. (2002) and Sinclair and Rufty (2012) reviewed agronomic experiments establishing the concave nitrogen yield response, with marginal yield gains typically declining from above one bushel per pound of applied nitrogen at low rates to well below half a bushel near agronomic optima.

These findings are consistent with steadily improving aggregate productivity but not with constant or improving nitrogen use efficiency at the margin. Lassaletta et al. (2014) reconstructed nitrogen use efficiency in cropping systems across 124 countries from 1961 to 2009 using paired estimates of crop nitrogen uptake and synthetic plus organic nitrogen inputs, and reported that global nitrogen use efficiency declined markedly over this period as application rates rose faster than uptake. For United States corn specifically, Monaco et al. (2025) used long-horizon regression on USDA Agricultural Chemical Use Program survey data and reported that the trend application rate increased from approximately 137 pounds per acre in 2002 to 152 pounds per acre by 2024, an increase of approximately 11 percent. Over the same period, the trend efficiency of nitrogen, measured as pounds of nitrogen per bushel produced, fell from 1.06 to 0.85, a 20 percent improvement attributable to faster yield growth than fertilizer growth (Monaco et al., 2025). The productivity pillar is therefore satisfied, though the literature notes that future gains will increasingly depend on efficiency rather than on rate increases (Cassman & Grassini, 2020).

Resilience pillar: weak or absent satisfaction

The evidence on the resilience pillar is sharply at odds with the conventional narrative that productivity gains in United States corn carry implicit gains in climate resilience. Schlenker and Roberts (2009) estimated a panel regression of United States county-level corn yields on growing-season temperature exposure, using fine-grained temperature distributions across the growing season. They found a strongly nonlinear relationship in which yields increase modestly up to approximately 29 degrees Celsius and decline sharply at higher temperatures, with the projected damage from end-of-century warming scenarios reaching 30 percent or more of average yields. Critically for the present analysis, Lobell et al. (2014) re-examined this relationship using United States Midwest data from 1995 to 2012 and found that the sensitivity of corn yields to vapor pressure deficit had increased over the period, with the regression coefficient on the drought-sensitivity term rising rather than falling as yields rose.

This is a destabilizing finding for the CSA narrative. It suggests that the very factors driving productivity growth, including higher planting densities and more closed canopies that maximize light interception, have also increased the crop's evaporative demand and therefore its vulnerability to drought stress (Lobell et al., 2014; Hatfield et al., 2011). Burke and Emerick (2016) used a long-difference regression strategy on United States county-level data over several decades to estimate the extent of long-run farmer adaptation to climate change. They found that long-run adaptation offsets only a modest share of short-run climate damages, with the bulk of climate-induced yield losses persisting in the long-run estimates. At the global level, Ortiz-Bobea et al. (2021) used a cross-country panel regression to estimate that anthropogenic climate change has slowed global agricultural total factor productivity growth by approximately 21 percent relative to a no-climate-change counterfactual, with North American agriculture among the more substantially affected regions. Hatfield et al. (2011) reviewed the climate impacts literature and concluded that further warming will compress the United States corn growing season and expose pollination to greater heat stress.

Taken together, the regression and modeling evidence supports the conclusion that input intensification is not a recognized resilience mechanism in United States corn and may, on the most credible recent econometric estimates, be a destabilizing factor. The resilience pillar is therefore not satisfied on the available evidence, and there is suggestive evidence that performance on this pillar has weakened over the very period in which productivity gains accelerated.

Mitigation pillar: clear failure

The evidence on the mitigation pillar is the most adverse for the CSA narrative. Agricultural soils are the largest United States source of nitrous oxide emissions, and the dominant proximate driver is synthetic nitrogen fertilizer applied to corn (Cavigelli et al., 2012; EPA, 2024). The IPCC Tier 1 emission factor assumes that approximately one percent of applied nitrogen is lost as direct nitrous oxide, with additional indirect emissions from leaching and volatilization (IPCC, 2019; Smith et al., 2014). The central empirical finding from the United States Midwest, however, is that this default linear relationship understates emissions at high nitrogen rates. Hoben et al. (2011) measured nitrous oxide fluxes from on-farm corn fields in Michigan across a wide range of nitrogen rates and fitted nonlinear regression models showing that emissions accelerate exponentially as rates approach and exceed agronomic optima. Shcherbak et al. (2014) extended this work in a global meta-analysis of 78 published studies and confirmed the nonlinear response, estimating that effective emission factors at high nitrogen rates can be approximately three times the default linear value.

This nonlinearity is the analytical hinge of the mitigation pillar verdict. Because the yield response to nitrogen is concave while the emissions response is convex, the ratio of emissions to yield, the emissions intensity per bushel, must rise with applied nitrogen beyond the efficiency optimum (Reay et al., 2012; Robertson et al., 2013; Snyder et al., 2009). Applying IPCC Tier 1 emission factors to representative United States corn rates of 140 to 150 pounds nitrogen per acre and yields of 170 to 180 bushels per acre yields emissions intensities in the range of approximately 14 to 16 kilograms of carbon dioxide equivalent per bushel, with substantial additional emissions from upstream fertilizer manufacturing through the Haber-Bosch process estimated at approximately 4 kilograms of carbon dioxide equivalent per kilogram of nitrogen (Snyder et al., 2009; Zhang et al., 2015). These intensities are not trending downward at a rate consistent with national mitigation targets. Cavigelli et al. (2012) reviewed United States agricultural nitrous oxide trends and reported that absolute emissions from cropland nitrous oxide have remained essentially flat or risen modestly since the early 2000s, while the share of national emissions attributable to nitrogen fertilizer has grown as other sectors have decarbonized. The mitigation pillar is therefore not satisfied.

Joint interpretation

Taken together, the three pillars produce a coherent asymmetric pattern. The productivity pillar is satisfied, with strong and convergent empirical support from regression-based yield trend analyses (Grassini et al., 2013; Kucharik & Ramankutty, 2005) and consistent agronomic understanding of the nitrogen response (Cassman et al., 2002). The resilience pillar is weakly or not satisfied, with credible recent regressions suggesting that climate sensitivity has increased rather than decreased alongside productivity gains (Burke & Emerick, 2016; Lobell et al., 2014; Ortiz-Bobea et al., 2021; Schlenker & Roberts, 2009). The mitigation pillar is not satisfied, with field experiments and global meta-analyses converging on the conclusion that high nitrogen application rates produce nonlinear emissions responses that erase any efficiency gains from yield growth (Hoben et al., 2011; Shcherbak et al., 2014; Snyder et al., 2009). This asymmetry, in which the same master input drives strong gains on one pillar and clear losses on another, is the central empirical finding of the paper.

8. Conclusion

This study has asked whether the United States Corn Belt production system, evaluated on its own stated terms against the Food and Agriculture Organization's three-pillar definition of climate-smart agriculture, passes the test. The analytical strategy was a structured framework analysis drawing on the existing empirical literature for each pillar, with particular attention to peer-reviewed regression and meta-analytic studies relating nitrogen fertilizer use to yield, yield stability, and emissions. The pattern that emerges is asymmetric: strong evidence of productivity gains, equivocal or weakening performance on resilience, and clear failure on the mitigation pillar.

Why the asymmetry matters

It is tempting to read an asymmetric result as a balanced verdict on United States corn: one pillar passed, one pillar indeterminate, one pillar failed. This reading, however, misses the definitional structure of the CSA framework. Lipper et al. (2014) and the FAO (2013) did not define climate-smart agriculture as a tallying of wins across independent dimensions. They defined it as the simultaneous satisfaction of three criteria. By construction, a system cannot be climate-smart if it fails one of the three pillars, any more than a structure can be sound if one of three load-bearing walls is missing. United States corn does not merely underperform on one CSA pillar; on the framework's own logic, it is not climate-smart at all, and the label should be withheld or heavily qualified in policy discourse until the asymmetry is resolved.

A deeper implication follows. The input that drives the productivity pillar is, in this system, the same input that drives the mitigation failure. There is no degree of freedom to solve one pillar without altering the other (Hoben et al., 2011; Shcherbak et al., 2014). This is a fundamentally different problem from the typical smallholder CSA case, in which the binding constraint is capital, information, or access, and in which pillar gains can often be stacked (Campbell et al., 2014; Paustian et al., 2016). In a mature, high-input system, the trade-off is structural. Addressing the mitigation pillar in a system like the Corn Belt requires either a substantial reduction in average nitrogen rates, a technological shift in nitrogen use efficiency of the kind Cassman and Grassini (2020) describe, a shift toward crop rotations and legume-based nitrogen, or a reconsideration of the downstream demand structures, particularly biofuel mandates, that sustain current production levels (Lark et al., 2020; Searchinger et al., 2008).

9. Policy implications

United States farm policy has increasingly incorporated climate-related language since the 2014 and 2018 Farm Bills, and the 2022 Inflation Reduction Act allocated historically large sums for agricultural conservation under the climate-smart heading. On the evidence reviewed here, these programs cannot accurately be described as making the United States corn system climate-smart unless they substantially alter the nitrogen management regime. Interventions that improve a single pillar without addressing the structural asymmetry risk converting the CSA concept from an analytical framework into a marketing tool, a risk that Lipper et al. (2014) explicitly warned against in the original articulation of the concept. The same scrutiny applies to the Renewable Fuel Standard, which has directed a substantial share of United States corn output into ethanol production since the 2007 expansion (Roberts & Schlenker, 2013; Searchinger et al., 2008). If the marginal bushel of corn ethanol is produced under conditions where the nitrogen-emissions curve has turned sharply upward, the policy's climate credentials depend critically on assumptions about where on that curve the marginal production occurs (Lark et al., 2020).

Limitations and future research

The principal limitation of the present study is that it depends on the existing empirical literature for each pillar. Where that literature is uneven across pillars, as it is in the resilience case, the analysis must report uncertainty rather than resolve it. A more granular farm-level analysis, drawing on USDA Agricultural Resource Management Survey microdata, would allow tighter estimates of the within-system relationships between nitrogen rate, yield, and emissions intensity. Process-based modeling using tools such as DAYCENT could refine the emissions estimates beyond the IPCC Tier 1 framework (Smith et al., 2014). Future research should also extend the three-pillar audit to alternative cropping systems, including soybean rotations and emerging cover-crop systems, to test whether the structural asymmetry identified here is unique to corn or generalizes across high-input cereal production. The most ambitious extension would be to develop a formal aggregation rule for the three pillars, since the present framework permits judgments about pillar satisfaction but not about overall system performance when pillars diverge.

The point of this exercise is not to discredit United States corn agriculture, which remains one of the most productive food systems in human history, nor to reject the climate-smart framework, which retains considerable analytical value when used precisely. The point is to take the framework at its word. When the three-pillar definition is applied to the archetype of industrial cereal production, it reveals a structural internal contradiction that more permissive uses of the label obscure. Frameworks exist to hold rhetoric accountable to data, and they lose their value when they are treated as labels to be claimed rather than as standards to be met.

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