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Embedded Seed Technology and Greenhouse Gas Emissions Reductions: A Meta-Analysis

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Agriculture's significant global contribution to greenhouse gas (GHG) emissions has spurred consumer and retailer interest in GHG mitigation and may lead to incentive programs for producers to lessen GHG emissions. Along those lines, a producer choice is the use of embedded seed technology designed to enhance the marketable portion of yield through improved disease, weed, and pest management with the same or lower use of inputs. This article examines commonalities and differences across three recent studies on rice, sweet corn, and cotton, which addressed the impacts of embedded seed technology on yield, input use, and GHG emissions. Embedded seed technology can be any method of improving the physical or genetic characteristics of a seed. These seed enhancements can include physiological quality, vigor, and synchronicity (consistency across seedlings in time of emergence and size) through traditional breeding, hybrid breeding, or biotechnology.

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Agriculture creates a significant source of greenhouse gas (GHG) emissions both in the United States and globally (Causarano et al., 2006; Lal, 2004; Nelson et al., 2009; Robertson, Paul, and Harwood, 2000). Agricultural production emits approximately 6.3% of U.S. GHG emissions according to the U.S. Environmental Protection Agency (EPA) (2011). When including all the upstream and indirect emissions from production of farm inputs, the total value is likely larger. Given increased consumer awareness and demand for products with lower GHG emissions coupled with the increasing reality of a government policy to lower net GHG emissions, row crop producers in the United States may have to adjust to both consumer demands and government requirements.

Comprehensive U.S. climate change legislation had never been closer to law than the House passage of the Waxman-Markey bill in 2008. Despite the demise of the bill in the Senate, the White House, the U.S. Department of Agriculture, and the EPA continue to support carbon emission reduction initiatives. Perhaps more importantly, agricultural producers face increasing demand to reduce GHG emissions associated with crop production from consumers, nongovernmental organizations, and from the retailers of their product. Eco- and carbon-labeling is on the rise; 34 carbon footprint labels existed globally in 2009 and the number is increasing (Baddeley, Cheng, and Wolfe, 2011). One survey found that 56.3% of U.S. consumer respondents and 64.4% of U.K. respondents desired climate impact information on their products (Bolwig and Gibbon, 2009).

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Although U.S. consumer demand lags that of the United Kingdom and Europe as a whole, agricultural producers that supply to global markets can expect to face increasing pressure from abroad regardless of U.S. demand or regulations.

Wal-Mart announced a potential plan to label each of its products with a sustainability index rating and has subsequently requested that every Wal-Mart supplier provide its GHG footprint, a direct measure of climate impact (Rosenbloom, 2009). In response to consumer demand for green products, many companies already differentiate their products with GHG emissions reductions. The Wal-Mart sustainability index may accelerate the adoption of GHG emission-lowering practices by suppliers to Wal-Mart and increase the need to lower GHG emissions throughout the supply chain, including production agriculture. Kellogg's recent carbon footprint assessment indicated that more than half of its products' carbon emissions are attributed to production of ingredients; hence, carbon footprint reductions up to the farm gate are important (Kellogg's, 2010). The Carbon Trust, a not-for-profit entity in the United Kingdom, has already labeled over 2800 products for carbon emissions (Bolwig and Gibbon, 2009). Tesco, the British-based supermarket chain, has begun carbon labeling some of its products and intends to expand efforts to all 70,000 of its products (Bridges, 2008). Both Japan and France have trial governmental programs in place for carbon labeling (Baddeley, Cheng, and Wolfe, 2011). At the same time, the International Standards Organization (ISO) has been developing an international standard (ISO 14067) on carbon footprinting (Baddeley, Cheng, and Wolfe, 2011). This will make it easier to create a common footprint value and label, which may reduce consumer confusion and uncertainty while at the same time increasing demand for low carbon products. With all of these efforts coming from different segments, one can expect that there will be growing pressure from numerous angles to reduce carbon emissions for agricultural products.

Agricultural producers are experiencing GHG polices at the field level as well. For example, since 2007, the California Rice Commission has worked with the Environmental Defense Fund to reduce the methane emissions associated with California rice production. As a result, a list of management practices that can reduce methane emissions was reviewed by the American Carbon Registry and the Verified Carbon Standard allows California rice producers to participate in voluntary carbon offset markets. Large purchasers of commodities are now directly working with industries or cooperatives to source commodities that have a green advantage so they can use them to market their goods as such.

Agricultural producers and processing industries may increase GHG emissions efficiency in preparation for increasing downstream pressure from industry and greater consumer demand for green or sustainable food products as well as mitigating a potential rise in fuel prices (fuel being a large carbon hotspot). One way producers and industries can reduce their GHG emissions is through the adoption of embedded seed technologies such as hybrid rice or transgenic cotton and corn.

Embedded seed technology can be any method of improving the physical or genetic characteristics of a seed that is contained in or on the seed itself. These seed enhancements can include physiological quality, vigor, and synchronicity through traditional breeding, hybrid breeding, or biotechnology. Hybrid breeding is conducted by crossing parent lines that are pure lines produced through inbreeding. Pure lines are plants that breed true or produce sexual offspring that nearly mimic their parents in all genetic traits. By crossing pure lines, a uniform population of F1 hybrid seed can be produced with predictable characteristics, which can often enhance yields, improve quality, and disease resistance. Genetically modified (GM) breeding (both cisgenic and transgenic) is conducted by adding a specific gene to a plant, or by knocking a gene with RNAi, to produce or reproduce a desirable phenotype. This can include the introduction of substances like Bacillus thuringiensis (Bt), which can produce resistance to some insects by encoding a protein that is toxic. Herbicide resistance, most notably glyphosate, can be engineered into plants by expressing a version of target protein that is not inhibited by the herbicide itself.

If adoption of embedded seed technologies results in production systems that require fewer trips across the field or fewer pesticide inputs, then it is expected that there will be reduced GHG emissions per acre and per unit of product produced as long as yields decline proportionately less than the input use reduction. Optimally, a decrease in inputs per acre would accompany an increase in yield per acre.

This article reviews three recent studies on rice, sweet corn, and cotton to address their individual impacts of embedded seed technology on yield, input use, and GHG emissions.

Rice

McFadden, Nalley, and Popp (2013) estimated the net carbon footprint (GHG emissions minus carbon sequestration) to produce 14 of the most commonly sown rice cultivars in six locations throughout the major rice-growing areas of Arkansas. The cultivars include conventional, Clearfield®, and hybrid cultivars. For purposes of this article, we exclude Clearfield® because it is designed primarily for red rice (*Oryza sativa* L.) control rather than reductions in input use (water) and enhancing yield. This study examined the potential for carbon footprint reduction and increase in the yield per unit of GHG emitted with the adoption of hybrid rice technology.

Sweet Corn

Nalley et al. (2013b) also reviewed the use of biotech sweet corn (Seminis® or Performance Series™ Sweet Corn, abbreviated PSSC here) targeted at controlling ear worm damage using fewer insecticide applications to reduce waste of sweet corn ears discarded because of worm damage and thereby increasing GHG efficiency both on a per-acre and per-ear basis. Fresh sweet corn provided an interesting case study for biotech versus GHG interactions because the potential for less insecticide applications and a lower GHG footprint could counteract consumer concerns about biotech in fresh produce. The analysis: 1) conducted a life-cycle inventory from preplant tillage to harvest to arrive at estimates of the carbon-equivalent (CE) GHG emissions of production practices for conventional versus PSSC sweet corn as adapted to the main sweet corn producing regions across the United States; 2) showcased the relative contribution to total GHG emissions of insecticides, fungicides, and herbicides (agrochemicals) and fuel use for production and irrigation; 3) determined the impact of reducing the number of insecticide applications on marketable yield from adoption of the embedded seed technology; and 4) quantified CE per acre and per ear of sweet corn.

Cotton

Finally, Nalley et al. (2013a) developed a cradle-to-gate[1] CE footprint of cotton using a scan level life-cycle analysis approach to GHG emissions across the range of seed technology available to cotton producers from 1997–2008. This study analyzed a single farm of approximately 7,000 acres in northeast Arkansas. This farm used numerous production methods and more importantly also had detailed production records. The analysis allowed calculation of GHG emissions per unit of cotton produced across a range of production practices associated with different seed technologies[2] over time. Advances in cotton breeding have simultaneously captured the benefits of both GHG reduction and reliance on fewer inputs. With the introduction and adoption of Bt cotton (Bollgard®, Bollgard II®, and Widestrike™) and glyphosate-tolerant cotton (Roundup Ready®, Roundup Ready® Flex), cotton production appears to have become less input-intensive while maintaining or increasing yields. The farm was typical of most mid-South cotton farms in that the 1997 crop was all conventional cotton with the gradual adoption of transgenic seed technology targeted specifically at herbicide

[1] Cradle-to-gate analysis means looking at the process including all of the inputs leading to the production. Typically life-cycle analysts will cut off those impacts that are below some threshold, for example less than 1% or 5% of total impact. Cradle-to-grave analysis includes the processing, transportation, use, and disposal or recycling of the product.

[2] Seed technologies included: conventional; Bollgard® Roundup Ready® and Bollgard II® Roundup Ready Flex®.

tolerance and plant expression of insecticidal toxins. In 2005 Bollgard® Roundup Ready® was adopted and in 2008 Bollgard II® Roundup Ready® Flex was adopted. Although data from all 12 years (1997–2008) were reviewed, only the three representative years were used in the study. These three years represented significant embedded seed technology milestones in commercial availability and grower adoption of transgenic technologies in that production region. For the purposes of this meta-analysis, only 1997 and 2008 are compared.

Literature and Methods

The potential role and economic feasibility of U.S. agriculture to mitigate GHG emissions has been the topic of previous studies. McCarl and Schneider (2007) suggested that agriculture provides a way to reduce GHG emissions until future technology can provide a solution to capture/trap or otherwise reduce GHGs. They argue that at carbon prices below $100 per ton, agriculture has a comparative advantage in offering GHG emission reductions compared with other industries. Furthermore, Schneider, McCarl, and Schmid (2007) suggested that reduced tillage and fertilization would be prevalent GHG reduction strategies at low carbon prices and that idling of land would commence at higher carbon prices to avoid GHG emissions from input use and soil GHG emissions.

Estimating a Carbon Footprint

All three studies used a life-cycle-based approach to assess multiple GHG emission in a standard unit of CEs (carbon footprint). Carbon emissions included both direct and indirect emissions. Direct emissions are those that come from on-farm operations. Examples are carbon dioxide emissions from diesel used by tractors and irrigation equipment, nitrous oxide emission from application of nitrogen (N) fertilizer, and methane release from flooding fields. Indirect emissions are generated off-farm as a result of manufacturing inputs used on the farm. An example of indirect emissions is the GHG emissions from natural gas to produce commercial fertilizer. Excluded from this study are embedded carbon emissions as a result of upstream production of equipment and tools used on-farm for agricultural production and any GHG emissions that may occur beyond the farm gate because these emissions are small and attributed to nonagricultural sectors.

Agriculture also has the potential to sequester atmospheric carbon. Sequestration can occur in the root mass and woody debris if tilled back into the soil. Additionally, the agricultural product itself can sequester carbon (Baker et al., 2007; Franzluebbers, 2005; Johnson et al., 2005; West and Marland, 2002). Tillage methods, cropping rotations, and soil type all can impact sequestration potential (Causarano et al., 2006). Nalley et al. (2012) found that soil type played the greatest role in affecting the levels of sequestration. For both the sweet corn and cotton studies (given their wide geographic variability), it was assumed soil carbon remained at equilibrium and so there was no net carbon sequestration or soil CO_2 emission. The rice study did however include soil carbon sequestration. Although rice was shown to sequester carbon, in this case, it did not alter the relative effects of total carbon emissions of conventional rice versus rice with embedded seed technology.

Carbon Equivalents

Given the multiple GHGs associated with global warming—principally N_20, CH_4, and CO_2—each of these gases was converted to their CE on the basis of their global warming potential to obtain a carbon footprint, a process stemming from a rich engineering literature on CE. CE factors and amounts per unit of input used for all three studies came primarily from EcoInvent using the IPCC (2007) 100-year methodology (EcoInvent Center, 2009; IPCC, 2007). These values estimate the emissions over the whole life cycle of the input, including production, transportation, delivery, and use. Some values were provided by Lal (2004), whereas a synthesis of numerous studies measuring carbon emissions from farm operations were used for all other inputs. The CE emissions estimated for diesel fuel combustion were provided by the U.S. EPA (U.S. EPA, 2009, 2011). For N fertilizers, CE footprint included

Table 1. Sources for Carbon Emission Values

	Cotton	Rice	Sweet Corn
Seed	N/A	N/A	EcoInvent
Fuel	U.S. EPA, EcoInvent	U.S. EPA, EcoInvent	U.S. EPA, EcoInvent
Fertilizers	Lal	Lal	EcoInvent
Lime	West and Marland	N/A	N/A
Pesticides	Lal	Lal	EcoInvent
Soil N_2O	Snyder et al. (1.28 lbs C/lb N)	Del Grosso et al. (2.18 lbs C/lb N)	IPCC (1.69 lbs/lb N)

N/A, not available for seed and not applicable for Lime; N, nitrogen.

both the natural gas resources needed in its production as well as indirect emissions of N_2O, a potent greenhouse gas resulting from the application of N fertilizer to the soil. Soil N_2O emissions have been identified as a major contributor to GHG emissions from crop production (Bouwman, 1996; Del Grosso et al., 2005; Smith, McTaggart, and Tsuruta, 1997; Snyder et al., 2009; Yanai et al., 2003). Although the methodologies for calculating carbon footprints were very similar across all studies, there were some differences that were too small to enumerate here. Table 1 summarizes emissions factors for inputs used across the three studies.

Methane emissions, a result of anaerobic decomposition of organic matter during flooding of rice, are the largest contributor to the total GHG emissions in paddy rice production. During flooding, CH_4 is released mainly through plants and decomposing stubble. The emitted quantity of CH_4 in paddy rice directly depends on two factors: aboveground dry matter and the number of days on flood, the latter varying by rice variety type. Methane emissions increase as the rice plant grows larger, reaches a peak, then later decreases as the plant nears the harvesting stage. Varieties that are flooded for a longer period release a greater quantity of CH_4. Typically four days after drainage, regardless of rice variety, a spike in CH_4 emission is noticed. This phenomenon is thought to occur because flooding is no longer a barrier for direct CH_4 emissions from soil to the atmosphere and is constant for each variety. The EPA published CH_4 emissions and acres harvested for rice cultivation in Arkansas for years 2005 through 2009 (U.S. EPA, 2011). Average CH_4 emissions per acre were derived from these data and further divided by the average days on flood for all varieties in Arkansas (83) to obtain CH_4 emissions per acre per day on flood as a function of the number of days on flood required by each cultivar.

Greenhouse Gas Emission Drivers across Production Practices by Crop Analyzed

Rice

The embedded seed technology in rice is between hybrid rice and conventionally or inbred rice. Over the past decade, the increased availability of hybrid rice seed (*Oryza sativa* L.) in the midsouthern United States has offered growers an alternative to conventional rice varieties historically planted in the United States. Commercially released in China during the Asian Green Revolution, the heterosis, or vigor, of first-generation (F1) hybrid rice has contributed greatly to Asian food security (Hazell, 2010). Hybrids can yield 15–20% more than conventional varieties on similar land as a result of the combination of yield-improving genetic traits in parent varieties (Yuan and Virmani, 1988). Rice producers in the mid-southern United States have rapidly adopted hybrids since their commercial release in 2000 (Bennett, 2011). Mid-southern U.S. hybrid acreage as a percentage of total harvested acreage has grown from 15% in 2005 to nearly 35% in 2011 (Durand-Morat, Wailes, and Chavez, 2011). Arkansas, the largest rice producer in the United States, accounts for two-thirds of the total hybrid rice acreage in the midsouthern states (Louisiana, Mississippi, Missouri, and Texas). Hybrid rice adoption in Arkansas has grown from 2% of harvested long-grain acreage in 2002 to nearly 50% in 2011. In addition to the hybrid rice yield advantage, Arkansas rice producers have adopted hybrid varieties because of their enhanced disease resistance packages and shorter vegetative stage, which can decrease input costs associated primarily with fuel use for irrigation.

Management practices have been found to have significant effects on GHG emissions from rice production. Changsheng et al. (2004) examined the effects of crop rotation, midseason drainage, tillage, straw amendment, percent of aboveground crop residue incorporation, and fertilizer type on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions. Crop rotation and percent of aboveground crop residue incorporation were the only two management practices found to have notable impacts on net CO_2 emissions. However, Changsheng et al. (2005) found switching from continuous flooding to midseason drainage reduced CO_2 emissions. Fertilizer type was the only management practice—out of those considered in the study—not found to have significant effects on CH_4 emissions but does play a large role with respect to CO_2 emissions. All management practices considered impacted N_2O emissions, although none were nearly as substantial as the impact of water management. These studies alert producers to the GHG emission differences in rice production management practices but do not address the potential GHG emission differences in rice cultivars. This is important because production practices and input requirements between rice cultivars (hybrid and conventional) are different and result in differences in GHG emissions per acre and per bushel of rice.

Sweet Corn

Field corn has been analyzed in depth from a life-cycle perspective (Kim and Dale, 2003; Landis, Miller, and Theis, 2007; Shapouri, Duffield, and Wang, 2002; West and Marland, 2002). However, relatively little literature exists with respect to sweet corn production and its effects of different production practices on life cycle and GHG impacts. Production practices (irrigation, tillage, cropping systems, and fertilization) can affect GHG generation by as much as a factor of 2.5 (Sainju, Jabro, and Stevens, 2008). In addition, seed variety and technology affect the level of inputs required as well as the effectiveness of such inputs on yield and yield loss. Marketable yield, the portion of ears harvested that is deemed marketable, is a key factor in producer production choices and is the dominant variable in assessing efficiency and sustainability of crop production (Negra et al., 2008).

Cotton

Although there are existing studies on GHG emissions from cotton production, there is a void in the literature on the effect of the adoption of advanced seed technology on total GHG emissions per acre and GHG emissions per pound of cotton lint produced. Nelson et al. (2009) summarized multiple crops (including cotton) on a county level under three tillage scenarios but did not address yield impacts. Nalley et al. (2012) addressed county-level emissions including yield results under different tillage practices on a national scale; however, the authors did not address the impacts of different imbedded seed technologies, which was the objective of the results reported within.

Data

Rice

Yield data were collected from the Arkansas Rice Performance Trials (ARPT) test plots that are located at six locations throughout the major rice-growing areas of Arkansas from 1997–2009 (University of Arkansas Cooperative Extension Service [UACES], 2010) for each cultivar.[3] The ARPT data consisted of four university-run experiment stations: Pine Tree (St. Francis County), Stuttgart (Arkansas County), Rohwer (Desha County), and Keiser

[3] It should be noted that these are paddy rice yields and not head rice yields (percent of rough rice that is milled and not broken). Although this study shows that hybrids have higher paddy yields, the initial hybrid lines had lower (1–2%) head rice yields. Most modern hybrids (like the ones in this study) have closed this gap through genetic breeding. Many things including chalk and climatic conditions can cause variations in head rice yield. That being said, this study assumes constant head rice yields for each cultivar.

(Mississippi County); and two test plots conducted by farmers in Jackson (Ahrent Farm) and Clay (Rutledge Farm) counties. A total of 14 cultivars were tested from 1997–2009. The cultivars for this analysis included eight conventional cultivars (four from the University of Arkansas and four from Louisiana State University) and three hybrid cultivars released by Rice-Tec (a private seed company). The experimental test plot yields likely exceed actual field yields, but unfortunately data for actual field yields by cultivar were not available. Nonetheless, Brennan (1984) argues that experimental test plots are the only reliable source of relative yields across cultivars. Therefore, the ARPT data allowed estimating the relative differences in sequestration between cultivars.

Sweet Corn

Data from university and private farm field trials performed at several locations in the Southeast and Midwest during the fall of 2009 through the summer of 2010 were provided by Monsanto. These locations included Wisconsin (Verona), Florida (Felda and University of Florida at Belle Glade), Illinois (Hinckley and University of Illinois at Urbana), two locations in Georgia (University of Georgia at Leesburg and Tifton), Mississippi (Leland), and Ohio (Ohio State University at Fremont). Corn was planted seasonally such that there were spring or fall harvest seasons, primarily in the southern locations, and a summer harvest season for the northern locations. At Felda, Florida, corn was harvested in both the spring and the fall.

Ultimately, for purposes of statistical comparison, the locations were segregated into two trials, a variety trial and a regional trial. The variety trial consisted of four season/location combinations: Felda fall, Felda spring, University of Georgia fall at Leesburg, and Mississippi fall. The main effect for the variety trial was insecticide use with treatment levels varying from either zero applications (*ZERO*), to once every 48 hours (*FULL*) after tasseling, or once every 96 hours (*HALF*) after tasseling. The subeffects were sweet corn hybrid (Obsession® versus Passion®) and seed technology (conventional [*CONV*] versus biotech [PSSC]). The data for these locations were balanced with two replicates for a total of 96 yield observations.

The regional trial consisted of three locations and two seasons (University of Georgia spring at Tifton, University of Florida at Belle Glade, spring and Verona, Wisconsin, summer). The regional trials were arranged as split plots with the main effect of insecticide and subeffect of seed technology. Passion® was the only variety used in the regional trials. This set of experiments was replicated four times but the data set was not balanced because the *HALF* insecticide treatment was not performed at Wisconsin. A total of 64 yield observations were analyzed for these comparisons.

Cotton

Using actual production records from a single northeast Arkansas farm with 113 fields, an estimate of direct GHG emissions from combustion of diesel and gasoline, N_2O emissions from N fertilizer as well as indirect emissions from embedded carbon in agrochemical, fertilizer, and fuel inputs was obtained. As such, estimates of average emissions per acre and per pound of lint yield weighted by their acreage for three growing seasons were calculated. Years differed primarily by cotton seed type (embedded seed technology) and tillage method, but irrigation type and agronomic conditions were held as constant as possible.

Fuel use was estimated for each piece of equipment using the Mississippi State Budget Generator. Based on equipment type, accessory, speed, efficiency, and other factors, gallons of diesel used per acre were estimated for each farming application (e.g., tilling, planting, spraying, and harvesting).

Conventional cultivars were grown under conventional tillage in 1997. No-till and reduced tillage were used in 2008 with the adoption of the newer seed technologies. Varieties sown in 2008 were Bollgard II® and Roundup Ready® Flex. Bollgard® technologies can reduce insecticide applications required to control certain caterpillar pests and Roundup Ready® technologies can reduce the number of herbicide applications and tillage operations.

Production records were available for 102 fields representing 6676 hectares in 2008. Most planted cultivars included the Bollgard II® embedded seed technology and all were Roundup Ready® Flex cultivars. Carbon equivalents were computed for active ingredients in applied fertilizers (N, phosphorus, potassium, sulfur, and boron), insecticides, herbicides, plant growth regulators, defoliants, and boll openers. Yield per acre was provided for each field from actual on-farm data across the 11-year period. However, given that yield in any year depends not only on inputs and cultivation practices, but also on environmental factors such as temperature, rainfall, and pest pressure, yield was adjusted for the representative years (1997 and 2008) to account for higher or lower production levels than typical. Those deviations were used to adjust all yields in that specific year: −18 lb/ac in 1997 and +58 lbs/ac in 2008. This represents a 2% yield adjustment to the actual average yield in 1997 (799 lbs/ac) and a 4.3% increase to the actual average yield in 2008 (1,291 lbs/ac). These adjustments were relatively small, indicating that the evaluated years were typical of the yield trend observed on the farm.[4]

Results

Rice

Methane emissions represent nearly half of total emissions for all seed types. Hybrid cultivars have the fewest days on flood and therefore have the lowest methane emissions. Aside from methane emissions, N fertilizer-associated N_2O emissions as well as emissions from diesel fuel used for flooding the field accounted for the majority of GHG emissions per acre. The hybrid cultivars yielded an average of 8730 lbs per acre (194 bushels per acre) and the conventional cultivars 8190 lbs per acre (182 bushels per acre). Associated carbon sequestration, consequently, had the hybrid cultivars sequester the most carbon at 753 lbs CE per acre followed by the conventional cultivars at 708 lbs CE per acre. Relatively lower diesel use, applied N, and days on flood combined with higher yields gave the hybrid cultivars lower emissions per bushel. Given their high yields and associated levels of soil carbon sequestration, the hybrid lines had the highest GHG efficiency or lowest carbon footprint per bushel ratio across all counties. The largest driver in the dollar per pound of carbon footprint ratio across cultivars would also be driven by yield.

Sweet Corn

Although regional differences exist as expected, the differences in per-acre emissions across insecticide management practice were quite small given small applications of active ingredient of insecticide per acre as well as low fuel use per acre for application of insecticide. Overall, fertilizer use dominated carbon footprint at each location and did not vary by seed technology or insecticide management practice.

Marketable yields showed vast differences across practices in both regional and variety trials. There were strong numerical differences across locations as well as differences by seed technology, variety, and insecticide. Use of biotechnology had a statistically significant effect on its own at $p < 0.05$ in the variety trials.

Use of PSSC embedded seed technology was superior to conventional (nonembedded) seed. Insecticide and variety effects, however, were not statistically significant. This suggests that producers choosing PSSC seed should be able to use less insecticide without a yield penalty regardless of variety chosen. PSSC seed performs better than conventional with no

[4] The Adjusted R^2 was 0.6 when fitting a linear form. Obviously it was not a perfect linear relationship but the yields trended up across time, most likely in a stairstep form for technological changes. There was only one observation per year so this methodology did not allow the authors to estimate alternative functional forms. The field-level yields were then adjusted by the model intercept and the estimated year coefficient. A new model was estimated with the adjusted yield as a function of year dummy variables with coefficients constrained to sum to zero. The coefficient for each of the three analyzed years could then be interpreted as a difference from the yield trend and was used as a constant to adjust observed field-level yields within each of the years. A salient point is that the yield adjustments were quite small, which indicated that the selected years were representative and not outliers resulting from uncontrolled factors such as weather.

significant differences across number of insecticide applications.

Overall these results suggest that the common practice of insecticide use to combat against ear worm damage is difficult given potential daily deposition of eggs near the top of the ear and subsequent hatching and migration of larvae under the husk where insecticides cannot reach. The use of biotechnology alleviates this issue and is statistically significantly at all levels of insecticide use and across variety.

The same statistical analysis was also performed for CE footprint per ear of marketable yield. Values using PSSC seed are consistently smaller than for conventional seed and the average values for the PSSC seed showed less variation in carbon footprint per ear numbers. This suggests that use of PSSC seed may add more consistency to carbon footprint per ear numbers because marketable yields are less prone to complete loss as a result of insect pests. Finally, like in the yield results, a lack of statistically significant differences across insecticide levels when using PSSC seed suggests that producers may safely switch from a conventional insecticide program to fewer applications and thereby enhance producer returns and lessen environmental impact without reducing marketable yield.

Cotton

It was found that on a CE per acre basis, which is solely a function of input use and not yield, GHG emissions are decreasing over time. For example, in 2008, 87% of all fields in the study had a CE per acre less than 490 lb/ac compared with just 1% meeting that GHG emissions threshold in 1997. Furthermore, when looking at the percentage of hectares in the study with a CE under 556 lb/ac, all acreage in 2008 qualified and only 78% qualified in 1997. These differences can be explained by the adoption of new seed technology, which altered production practices and thus input use. This phenomenon can be explained by the amount of diesel fuel use (a function of passes in the field to apply inputs), which is decreasing over time. Also, the amount of agrochemicals decreased over time as well as the variance from one field to the next. This would make intuitive sense; with conventional cotton (not Bollgard®), one would have to spray only the infested fields but not others. In the interval from 1997 to 2005, the Arkansas Boll Weevil Eradication Program had essentially eliminated the boll weevil from this production area. Boll weevils were not significant pests in northeast Arkansas like in other parts of the state because of winter kill and limited overwintering habitat, but there were reductions in insecticide use associated with eradication and thus some of the reduced GHG can be attributed to the eradication of boll weevils.

Although these results in themselves are encouraging news for the environment, it is ignoring the gains in yield brought about by seed technological advancements. The ratio of kilograms of GHG per kilogram of cotton is a more holistic view of GHG reduction improvement as it tracks all efficiency improvement over time. Compared with the average of 1997 yields of 799 lbs lint per acre, yield increased by 61% in 2008. There are many factors that contribute to higher yields (management practices, more efficient use of inputs, and climatic issues) along with advanced breeding and embedded seed technology. Advancements of seed technology alone certainly do not account for the entire growth in yield over time, but they likely account for a large portion. Additionally, weed control advancements were accomplished simply by a post-emergence application of the Roundup herbicide on Roundup Flex cotton rather than more time-consuming tillage operations. This weed management option allowed producers to move rapidly from crop establishment to "lay by." At that point they could begin to apply irrigation, which allowed them to avoid water deficit stress in the critical period before first flower. It is important to note that yield potential is set by the plant structure at first flower. In a conventional tilled field, often the crop was stressed because producers were spending their time killing weeds (and sometimes insects not controlled by Bt such as boll weevil and plant bugs) rather than allocating time to best management practices.

The amount of GHG (CE) to produce one pound of cotton has steadily decreased from

Table 2. Summary of GHG Efficiency Gains as a Function of Yield and Input Use Changes

Rice	Conventional	Hybrid	Change
Yield (lb/ac)	8179	8721	7%
GHG (lb CE/ac)	1320	1146	–13%
GHG/yield (lb CE/lb)[a]	0.17	0.14	–15%
Sweet Corn	Conventional	PSSC	Change
Yield (ears/ac)	11,305	19,772	75%
GHG (lb CE/ac)	823	810	–2%
GHG/yield (lb CE/ears)[a]	0.11	0.04	–61%
Cotton	Conventional	BG2 RR Flex	Change
Yield (lb/ac)	799	1291	61%
GHG (lb CE/ac)	521	452	–13%
GHG/yield (lb CE/lb)[a]	0.67	0.34	–49%

[a] GHG/yield may not calculate directly as GHG/yield because the authors used weighted averages that are not available here.
GHG, greenhouse gas; CE, carbon equivalent.

1997–2008. Again, this is a function of increased yields and decreased inputs. In 1997 (with conventional cultivars), it took approximately 0.67 lb of CE to produce 1 lb of cotton lint. That number decreased 49% (compared with 1997) to 0.34 lb of CE in 2008 (with Bollgard® Roundup Ready® II) (Table 2). Furthermore, 99% of fields in 2008 had a CE per pound of cotton lower than 0.5 compared with just 3% in 1997. By any standards, this is a significant reduction in the amount of GHG required in cotton production. Although the impact of changing levels in irrigation and soil carbon sequestration was not measured in this study, they are expected to counteract each other in the sense that higher irrigation would use more fuel and hence add to emissions, whereas higher yields would offset these emissions through heightened sequestration. Spatially these differences across fields in a given year did not matter but over time irrigation use may have increased marginally.

Summary

Table 2 summarizes the yield and input use changes for the various crops analyzed in this article. It shows that GHG efficiency gains were attained and somewhat equally so with yield and input use changes in rice and cotton, whereas changes in ear worm damage and therefore marketable yield dominated efficiency gains in sweet corn.

Conclusions

Although CE GHG emissions per acre are important in terms of assessing environmental aspects of production, per-acre measures ignore the productivity of a field and thus how efficient a producer is at using each unit of GHG. Thus, the ratio of pounds of GHG per unit of output is a more holistic view of GHG reduction progression through time. The adoption of hybrid rice on average increased yield with a measurable decrease in inputs given the shorter duration under flood leading to fewer methane emissions and also water use saving emissions from diesel-powered pumping stations. Thus, the environmental benefit of hybrid rice (in terms of GHG emissions) is a decrease in GHG/bu of rice. Similarly, with the adoption of GM cotton, it appears that yields have increased dramatically over the course of ten years as a result of the embedded seed technology and attendant production practices and inputs have decreased as well. The environmental benefits of GM cotton are seen through a reduction of inputs, which on average have lowered GHG per pound of cotton by 49% in Arkansas. Sweet corn provides an interesting result in that the adoption of embedded seed technology in sweet corn significantly improves marketable yield by reducing ear worm damage with a decrease in input use that is relatively small from a GHG perspective but large from a production profitability perspective. Across all locations adopting embedded seed technology, producers could reduce their GHG per ear of marketable corn by up to 61%. Furthermore, this efficiency increase is observable from one production period to the next.

Although companies like Monsanto and RiceTec do not release seed technology based solely on its environmental benefits, it appears that some hybrid and GM varieties may possess some environmental benefits. Ultimately, the adoption of these seed technology advancements will rest with economic feasibility for the producer in the sense that seed cost will be higher and will need to be offset by efficiency gains and perhaps market premiums. Again, increased consumer awareness and demand for products with lower GHG emissions coupled with the increasing reality of a government policy to lower net GHG emissions, the entire food and fiber supply chain may have to adjust. If adoption of embedded seed technologies such as hybrid or GM seeds results in production systems that require fewer trips across the field or fewer pesticide inputs, then GHG emissions per acre and per unit of product produced should decrease given these results. Furthermore, seed technology adoption is relatively straightforward from a production management perspective because no new equipment needs or other technical barriers to adoption exist.

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