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Regenerative agriculture: merging farming and natural resource conservation profitably

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Most cropland in the U.S. is characterized by large monocultures, whose productivity is maintained through a strong reliance on costly tillage, external fertilizers, and pesticides (Schipanski et al., 2016). Despite this, farmers have developed a regenerative model of farm production that promotes soil health and biodiversity, while producing nutrient-dense farm products profitably. Little work has focused on the relative costs and benefits of novel regenerative farming operations, which necessitates studying *in situ*, farmer-defined best management practices. Here, we evaluate the relative effects of regenerative and conventional corn production systems on pest management services, soil conservation, and farmer profitability and productivity throughout the Northern Plains of the United States. Regenerative farming systems provided greater ecosystem services and profitability for farmers than an input-intensive model of corn production. Pests were 10-fold more abundant in insecticide-treated corn fields than on insecticide-free regenerative farms, indicating that farmers who proactively design pest-resilient food systems outperform farmers that react to pests chemically. Regenerative fields had 29% lower grain production but 78% higher profits over traditional corn production systems. Profit was positively correlated with the particulate organic matter of the soil, not yield. These results provide the basis for dialogue on ecologically based farming systems that could be used to simultaneously produce food while conserving our natural resource base: two factors that are pitted against one another in simplified food production systems. To attain this requires a systems-level shift on the farm; simply applying individual regenerative practices within the current production model will not likely produce the documented results.

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3 **Regenerative agriculture: merging farming and natural resource conservation profitably.**

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17 **Abstract.** Most cropland in the U.S. is characterized by large monocultures, whose productivity is
18 maintained through a strong reliance on costly tillage, external fertilizers, and pesticides (Schipanski et
19 al., 2016). Despite this, farmers have developed a regenerative model of farm production that promotes
20 soil health and biodiversity, while producing nutrient-dense farm products profitably. Little work has
21 focused on the relative costs and benefits of novel regenerative farming operations, which necessitates
22 studying *in situ*, farmer-defined best management practices. Here, we evaluate the relative effects of
23 regenerative and conventional corn production systems on pest management services, soil conservation,
24 and farmer profitability and productivity throughout the Northern Plains of the United States.
25 Regenerative farming systems provided greater ecosystem services and profitability for farmers than an
26 input-intensive model of corn production. Pests were 10-fold more abundant in insecticide-treated corn
27 fields than on insecticide-free regenerative farms, indicating that farmers who proactively design pest-
28 resilient food systems outperform farmers that react to pests chemically. Regenerative fields had 29%
29 lower grain production but 78% higher profits over traditional corn production systems. Profit was
30 positively correlated with the particulate organic matter of the soil, not yield. These results provide the
31 basis for dialogue on ecologically based farming systems that could be used to simultaneously produce
32 food while conserving our natural resource base: two factors that are pitted against one another in
33 simplified food production systems. To attain this requires a systems-level shift on the farm; simply
34 applying individual regenerative practices within the current production model will not likely produce the
35 documented results.


36 **Key words:** agroecology, biodiversity, conservation agriculture, corn, pest management, profit, soil
37 organic matter, yield.


38 **Introduction.** Development of synthetic fertilizers, hybrid crops, genetically modified crops, and
39 policies that decouple farmer decisions from market demands all helped create a modern food
40 production system which reduces the diversity of foods that are produced (Fausti and Lundgren, 2015;
41 Pretty, 1995). This simplification of our food system contributes to climate change (Carlsson-Kanyama and
42 Gonzalez, 2009), rising pollution (Beman et al., 2011; Morrissey et al., 2015), biodiversity loss (Butler et
43 al., 2007; Landis et al., 2008), and damaging land use changes (Johnston, 2014; Wright and Wimberly,
44 2013) that affect the sustainability, profitability and resilience of farms (Schipanski et al., 2016). Farmers
45 experience the highest suicide rate of any profession in the United States, a rate nearly five-fold higher
46 than the general public (McIntosh et al., 2016); the driving depression rates are related to conventional
47 production practices (Beard et al., 2014). Yet the scale of our food production system provides
48 opportunities for solving some of these planetary scale problems (Lal, 2004; Teague et al., 2016), but
49 requires a systems-level shift in the values and goals of our food production system that de-prioritizes
50 solely generating high yields toward one that produces higher quality food while conserving our natural
51 resource base.

52 The goal of regenerative farming systems (Rodale, 1983) is to increase soil quality and biodiversity in
53 farmland while producing nourishing farm products profitably. Unifying principles consistent across
54 regenerative farming systems include 1) abandoning tillage (or actively rebuilding soil communities
55 following a tillage event), 2) eliminating spatio-temporal events of bare soil, 3) fostering plant diversity on
56 the farm, and 4) integrating livestock and cropping operations on the land. Further characterization of a
57 regenerative system is problematic because of the myriad combinations of farming practices that
58 comprise a system targeting the regenerative goal. Other comparisons of conventional agriculture with
59 alternative agriculture schemes do not compare *in situ* best management practices developed by
60 farmers, and frequently ignore a key driver to decision making on farming operations: the examined
61 systems' relative net profit to the farmer (De Ponti et al., 2012).

62 **Materials and Methods.** Corn (*Zea mays* L.) was selected for our study due to its pre-eminence as a
63 food crop in North America and globally. Corn is planted on 39.9% of all crop acres (NASS, 2017), or 4.8%
64 (37.1 million ha) of the terrestrial land surface of the contiguous 48 states. In 2012, it generated 30.3%
65 (\$64,319 billion) of all gross crop value in the U.S. (NASS, 2017). Nearly 100% of cornfields are treated
66 annually with insecticides (NASS, 2017). We used a matrix of specific production practices (Table S1) to
67 define each farm into one of two systems (regenerative or conventional). The most regenerative systems
68 used mixed multispecies cover crops (ranging from 2-40 plant species), were never-till, used no
69 insecticides, and grazed livestock on their cropland. The most conventional farms practiced tillage at least
70 annually, applied insecticides (as GM insect-resistant varieties and neonicotinoid seed treatments), and
71 left their soil bare aside from the cash crop.

72 Soil organic matter, insect pest populations, and corn yield and profit were assessed for each field.
73 Soil cores (8.5 cm deep, 5 cm in diameter; 30 g of soil each; n = 4 samples per field that were made a
74 composite sample; only one field was sampled per farm and two farms were omitted) were collected at
75 least 10 m from one another during anthesis. Samples were cleaned of plant residue, ground, and dried
76 to constant weight at 105° C. Particulate soil organic matter (POM) was determined by screening each
77 sample (soaked in 5 g L⁻¹ aqueous hexametaphosphate) through 500 um (course POM) and 53 um (fine
78 POM) sieves and then applying the loss on ignition (LOI) technique (Davies, 1974). Insect pests were
79 enumerated through dissections of all aboveground plant tissues (25 plants per field). Major pests of
80 corn (rootworm adults, caterpillar pests, and aphids) are all present in cornfields at this crop
81 developmental stage (Lundgren et al., 2015). Yields were gathered from three 3.5 m sections of row from
82 each field. Gross revenue for each field were considered as yield and return on grain, and additional
83 revenue streams (e.g., livestock grazing). Total direct costs for each field were calculated based on the
84 costs of corn seed, cover crop seed, drying/cleaning grain, crop insurance, tillage, planting, fertilizers,
85 pesticides, and irrigation.

86 **Results and Discussion.**  Insect pest populations were more than 10 fold higher on the insecticide-
87 treated farms than on the insecticide-free regenerative farms (ANOVA; $F_{1,77} = 13.52$, $P < 0.001$; Figure 1).
88 Pest problems in agriculture are often the product of low biodiversity and simple community structure on
89 numerous spatial scales (Tscharntke et al., 2012). Hundreds of invertebrate species have been inventoried
90 from cornfields of the Northern Plains of the U.S. (Lundgren et al., 2015; Welch and Lundgren, 2016), but
91 these communities represent only 25% of the insect species that lived in ancestral habitats (e.g., prairie)
92 that cornfields replaced in this region (Schmid et al., 2015). Pest abundance is lower in cornfields that
93 have greater insect diversity, enhanced biological network strength and greater community evenness
94 (Lundgren and Fausti, 2015). Suggested mechanisms to explain how invertebrate diversity and network
95 interactions reduce pests include predation (Letourneau et al., 2009), competition (Barbosa et al., 2009),
96 and other processes that may not be easily predicted. What practices foster diversity in agroecosystems?
97 In our studies, farmers that replaced insecticide use with agronomic forms of plant diversity invariably
98 had fewer pest problems than those with strict monocultures. Reducing insect diversity and relying solely
99 on insecticide use establishes a scenario whereby pests persist and resurge through adaptation, as was
100 observed by our forebears (Perkins, 1982; Stern et al., 1959). Applying winter cover crops (Lundgren and
101 Fergen, 2011), lengthening crop rotations (Bullock, 1992), diversifying field margins using conservation
102 mixes (Haaland et al., 2011), and allowing or promoting non-crop plants between crop rows (Khan et al.,
103 2006) are other agronomically sound practices that regenerative farmers successfully apply to improve
104 the resilience of their system to pest proliferation.

105 Despite having lower grain yields, the regenerative system was nearly twice as profitable as the
106 conventional corn farms (ANOVA; $F_{1,70} = 14.35$, $P < 0.001$; Figure 2). Regenerative farms produced 29%
107 less corn grain than conventional operations (8481 ± 684 kg/ha vs. $11,884 \pm 648$ kg/ha; ANOVA;
108 $F_{1,70} = 8.39$, $P = 0.01$). Yield reductions are commonly reported in more ecologically based food
109 production systems relative to conventional systems (De Ponti et al., 2012). However, only 4% of calories
110 produced as corn grain is eaten directly by humans, and almost none is consumed as grain.  36% of grain

111 is fed to livestock (NASS, 2017), and corn-fed beef contains only 13% of the total calories produced by
112 corn grain. Two ways that regenerative systems could increase the human food produced per ha in
113 cornfields would be to increase the diversity of livestock on the field, or increasing the duration of grazing
114 current stock. The relative profitability in the two systems was driven by the high seed and fertilizer costs
115 that conventional farms incurred (32% of the gross income went into these inputs on conventional fields,
116 versus only 12% in regenerative fields), and the higher revenue generated from grain and **other products**
117 **produced** on the regenerative corn fields (Figure 2). The high seed costs on conventional farms are largely
118 attributable to premiums paid by farmers for **prophylactic insecticide traits**, whose value is questionable
119 due to pest resistance and persistent low abundance for some targeted pests in the Northern Plains
120 (Hutchison et al., 2007; Krupke et al., 2017). Regenerative farmers reduced their fertilizer costs by
121 including legume-based cover crops on their fields during the fallow period (Ebelhar et al., 1984),
122 adopting no-till practices (Lal et al., 2007), and grazing the crop field with livestock (Russelle et al., 2010).
123 They also received higher value for their crop by **receiving an organic premium**, by selling their grain
124 directly to consumers as seed or feed, and by extracting more than just corn revenue from their field
125 (e.g., by grazing cover mixes with livestock).

126 The profitability of a corn field was not related to grain yields ($F_{1,70} < 0.001$; $P = 0.98$; $r^2 < 0.01$;
127 $\text{profit} = -0.0006[\text{yield}] + 1274$), but was positively correlated with the level of POM in the soil, and
128 inversely related to the bulk density of the soil (Figure 3). Organic matter is considered by some as the
129 basis for productivity in the soil (Karlen et al., 1997; Tiessen et al., 1994), and soils with high SOM
130 typically have lower bulk density. SOM increases water infiltration rates, and supports greater microbial
131 and animal abundance and diversity (Lehman et al., 2015). The components of POM are the labile
132 portion of this SOM, and are frequently used to study the effects of management-based differences in
133 SOM (Cambardella and Elliott, 1992). The **only way to** generate SOM in cropland is through fostering
134 biology, which inherently is driven by plant communities through sequestration of CO_2 from the
135 atmosphere. Eliminating tillage (Pikul et al., 2007; Six et al., 1999), implementing cover crops (Ding et al.,

136 2006; Kuo et al., 1997), and cycling plant residue through livestock (Tracy and Zhang, 2008) all enhance
137 this process, and all are important practices used in regenerative food systems that raise POM in the soil.

138 **Conclusions.** The farmers themselves have devised an ecologically based production system
139 comprised of multiple practices that are woven into a profitable farm that promotes ecosystem services.
140 Regenerative farms fundamentally challenge the current food production paradigm that maximizes gross
141 profits at the expense of net gains for the farmer. Key elements of this successful approach to farming
142 include

- 143 1) By promoting soil biology and organic matter and biodiversity on their farms, regenerative
144 farmers required fewer costly inputs like insecticides and fertilizers, and managed their pest
145 populations more effectively.
- 146 2) Soil organic matter was a more important driver of proximate farm profitability than yields were,
147 in part because the regenerative farms marketed their products differently or had a diversified
148 income stream from a single field.

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158

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260 wetlands. *Proceedings of the National Academy of Sciences of the U.S.A.* 2013; 110: 4134-4319.

261 **Figure 1. Insecticide-treated cornfields had higher pest abundance than untreated, regenerative**
262 **cornfields.** Values presented are mean \pm SEM total pests (corn rootworm adults, European corn borers,
263 Western bean cutworm, other caterpillars, and aphids) per m², and were assessed during corn anthesis.
264 The systems were regarded as best-management practices for the sampled region by the farmers
265 themselves. All conventional farms planted neonicotinoid-treated, Bt corn seed to prophylactically
266 reduce pests, and some cornfields were also sprayed with insecticides. Regenerative farms included >3 of
267 the following practices: use of a multispecies cover crop, abandonment of insecticide, abandonment of
268 tillage, and the cropland was grazed, etc. Pest abundance was significantly different in the two systems
269 ($\alpha = 0.05$; $n = 39$ regenerative cornfields and 40 conventional cornfields).

270 **Figure 2. Regenerative corn fields generate nearly twice the profit of conventionally managed corn**
271 **fields.** Profit was calculated using direct costs and revenues for each field and excludes any overhead and
272 indirect expenses. Regenerative cornfields implemented three or more practices such as planting a
273 multispecies cover mix, eliminating pesticide use, abandoning tillage, and integrating livestock onto the
274 crop ground. Conventional cornfields used fewer than two of these practices. The regenerative systems
275 had 70% higher profit than conventional cornfields ($\alpha = 0.05$; $n = 36$ fields in each system).

276 **Figure 3. Corn fields with high particulate organic matter and low bulk density in the soil have greater**
277 **profits.** Corn fields were managed under either conventional or regenerative systems, and profit was
278 calculated using direct costs and revenues for each field and excludes any overhead and indirect
279 expenses. (general linear regression model; $F_{1,16} = 7.84$; $P = 0.01$; $r^2 = 0.34$; profit = $29.68[\text{POM}] - 66.94$;
280 bulk density; $F_{1,19} = 5.23$; $P = 0.03$; $r^2 = 0.24$; profit = $-975 [\text{POM}] + 1593$)

281 **Table S2. Soil organic matter on regenerative and conventional corn farms.**

Reference town	Farm locations (latitude, longitude)	SOM (g/kg)
Bladen, NE	40.31971, -98.57358	6.23
Bladen, NE	40.33703, -98.56301	4.52
York, NE	40.63054, -97.66534	6.21
York, NE	40.97390, -97.49031	5.55
Bismarck, ND	46.85280, -100.60131	4.19
Bismarck, ND	46.85280, -100.35145	N/A
Bismarck, ND	46.81734, -100.51257	5.82
Bismarck, ND	47.14250, -100.19720	3.85
White, SD	44.42572, -96.58806	N/A
White, SD	44.41155, -96.60008	5.52
Pipestone, MN	44.11446, -96.32468	N/A
Pipestone, MN	44.12416, -96.36422	4.75
Toronto, SD	44.59248, -96.57923	7.60
Toronto, SD	44.57960, -96.58367	6.38
Gary, SD	44.80565, -96.34708	7.53
Gary, SD	44.80689, -96.35465	7.36
Arlington, SD	44.41566, -97.18795	8.17
Arlington, SD	44.42644, -97.25077	8.18
Lake Norden, SD	44.58976, -97.08649	4.56
Lake Norden, SD	44.55.6839, -97.243820	6.26

Figure 1

Figure 1. Insecticide-treated cornfields had higher pest abundance than untreated, regenerative cornfields.

Values presented are mean \pm SEM total pests (corn rootworm adults, European corn borers, Western bean cutworm, other caterpillars, and aphids) per m², and were assessed during corn anthesis. The systems were regarded as best-management practices for the sampled region by the farmers themselves. All conventional farms planted neonicotinoid-treated, Bt corn seed to prophylactically reduce pests, and some cornfields were also sprayed with insecticides. Regenerative farms included >3 of the following practices: use of a multispecies cover crop, abandonment of insecticide, abandonment of tillage, and the cropland was grazed, etc. Pest abundance was significantly different in the two systems ($\alpha=0.05$; n = 39 regenerative cornfields and 40 conventional cornfields).

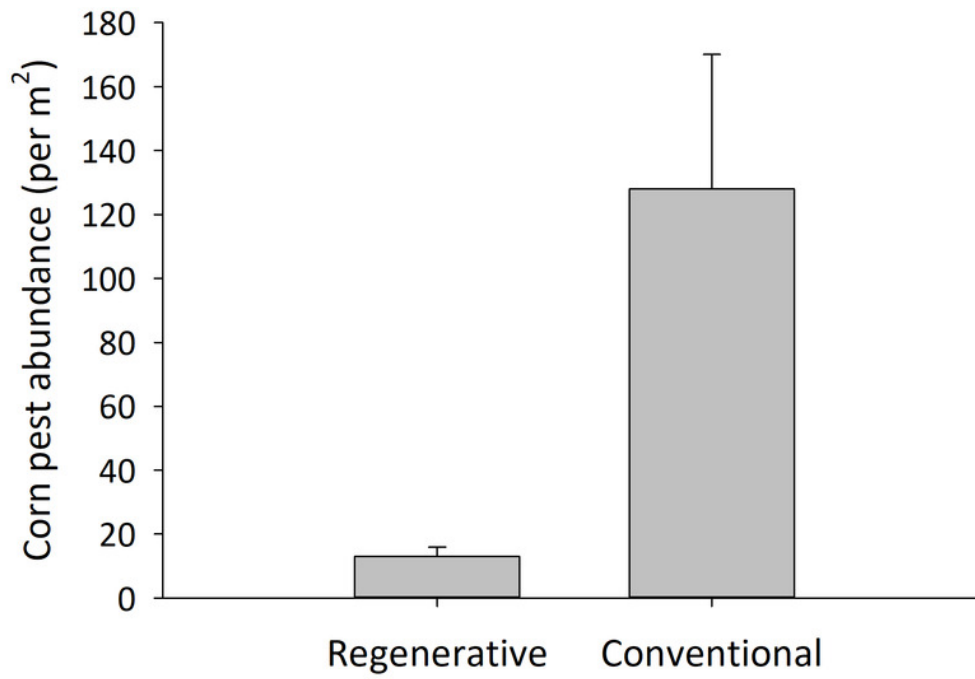


Figure 2

Figure 2. Regenerative corn fields generate nearly twice the profit of conventionally managed corn fields.

Profit was calculated using direct costs and revenues for each field and excludes any overhead and indirect expenses. Regenerative cornfields implemented three or more practices such as planting a multispecies cover mix, eliminating pesticide use, abandoning tillage, and integrating livestock onto the crop ground. Conventional cornfields used fewer than two of these practices. The regenerative systems had 70% higher profit than conventional cornfields ($\alpha=0.05$; $n = 36$ fields in each system).

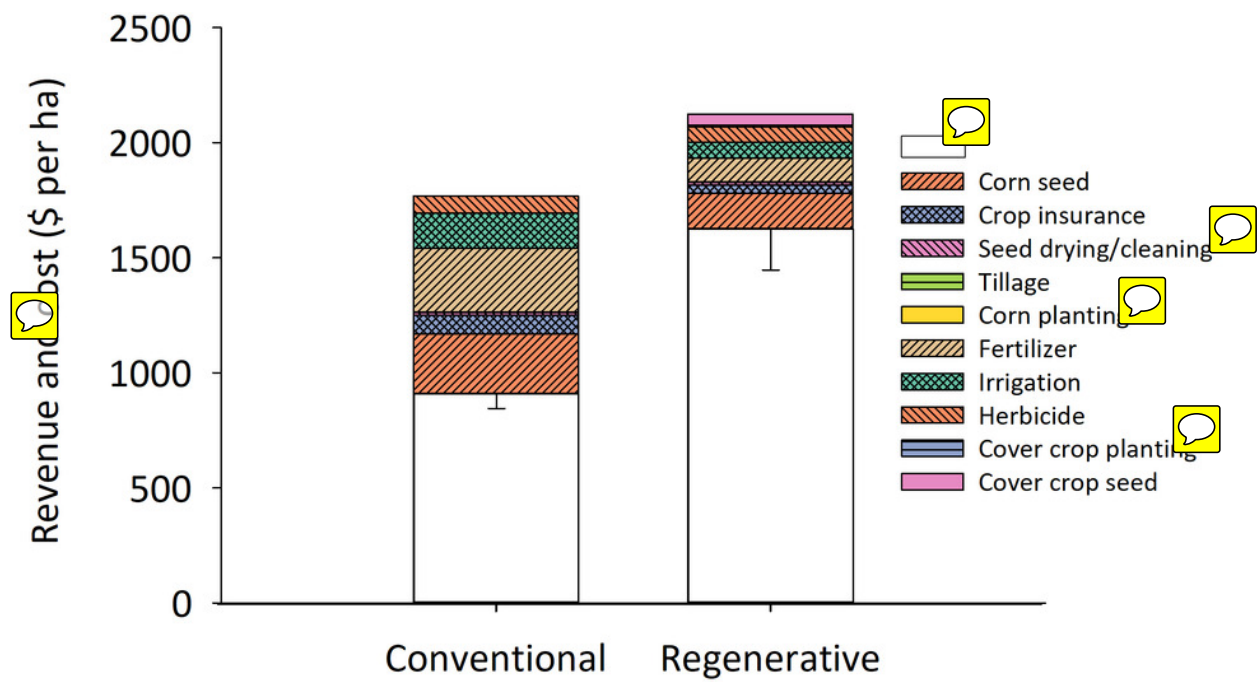


Figure 3

Figure 3. Corn fields with high particulate organic matter and low bulk density in the soil have greater profits.

Corn fields were managed under either conventional or regenerative systems, and profit was calculated using direct costs and revenues for each field and excludes any overhead and indirect expenses. (general linear regression model; $F_{1,16}=7.84$; $P=0.01$; $r^2=0.34$; profit= $29.68[\text{POM}] - 66.94$; bulk density; $F_{1,19}=5.23$; $P=0.03$; $r^2=0.24$; profit= $-975 [\text{POM}] + 1593$)

