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Energy Profiles of an Agricultural Frontier: The American Great Plains, 1860–2000

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Abstract

Agro-ecosystem energy profiles reveal energy flows into, within, and out of U.S. Great Plains farm communities across 140 years. This study evaluates external energy inputs such as human labor, machinery, fuel, and fertilizers. It tracks the energy content of land produce, including crops, grazed pasture, and firewood, and also accounts unharvested energy that remains available for wildlife. It estimates energy redirected through livestock feed into draft power, meat, and milk, and estimates the energy content of final produce available for local consumption or market sale. The article presents energy profiles for three case studies in Kansas in 1880, 1930, 1954, and 1997. Two energy transformations occurred during that time. The first, *agricultural colonization*, saw farm communities remake the landscape, turning native grassland into a mosaic of cropland and pasture, a process that reduced overall landscape energy productivity. A second energy transition occurred in the mid-twentieth century, characterized by fossil fuel energy imports. That outside energy raised harvested and unharvested energy flows, reused biomass energy, and also final produce. This *socio-ecological transition* increased landscape energy productivity by 33 to 45 percent above pre-settlement conditions in grain-growing regions. These energy developments were not uniform across the plains. Variations in rainfall and soil quality constrained or favored energy productivity in different places. The case studies reveal the spatial variation of energy profiles in Great Plains agro-ecosystems, while the longitudinal approach tracks temporal change.

Keywords

agro-ecosystem energy; Great Plains agriculture; agricultural colonization; socio-ecological transition

Introduction

For 10,000 years agriculture has been society's primary energy supplier (Malanima 2006 and 2009; Simmons 2008). Food for subsistence, firewood for domestic heat and industrial charcoal, a transportation system based on draft animals—all originated in agro-ecosystems. Even cities imported food, livestock feed, and fuel from hinterland farms (Cronon 1991; Gingrich 2012). Maintaining agro-ecosystems required a constant investment of energy, in the form of human labor, farm produce cycled through livestock, or imported energy-rich inputs. Agro-ecosystems are societal converters that supply, consume, and re-direct energy through looped pathways. The American Great Plains presents a rare opportunity for analysis: an agricultural frontier well documented from its beginning 150 years ago and right through the socio-ecological transition to modern industrialized farming. Agricultural frontiers date to the beginning of agriculture, but their incidence rose during the nineteenth century due to European colonization. In places Crosby (1986) referred to as “neo-Europes,” settlers displaced Indigenous populations and carried out large-scale land conversion for agriculture. Examples occurred in the Americas, Australia, and New Zealand, but also in the Ukrainian and Russian steppes (Moon 2013). Compared to long-farmed places, frontiers present a unique agricultural context. Large labor investments converted forests and grasslands into managed agro-ecosystems. Settlers exploited rich soils to grow bumper crops with little re-investment in fertility maintenance. Labor shortages, of both people and draft animals, made it advantageous to open new land rather than re-invest in old land (Grigg 1992; Federico 2005; Belich 2009). Between 1860 and 2000, the Great Plains underwent two energy transitions. *Agricultural colonization* converted a grassland biome into an agricultural landscape by the 1920s, reducing overall plant growth in the process. Then by the 1960s a *socio-ecological transition* added imported fossil fuel energy to what had been primarily a local, biomass-based energy regime (Fischer-Kowalski and Haberl 2007). Inexpensive energy washed through the system, multiplying energy outputs, but also boosting internal and unharvested biomass energy flows.

The energy profiles presented here (Table 1) reveal core energy dynamics of Great Plains agro-ecosystems in 1880, 1930, 1954, and 1997; see the Appendix for energy estimation methods using historical sources (Tello et al. 2015). Prior to Euro-American settlement, c. 1850, grassland ecosystems stockpiled energy as native vegetation, providing a baseline comparison with the agro-ecosystems that followed. Adopting Human Appropriation of Net Primary Production (HANPP) terminology (Haberl et al. 2007; Erb et al. 2009; Krausmann et al. 2013), pre-settlement potential vegetation (NPP_{pot}) estimates aboveground Net Primary Production of grassland plants under Native American fire regimes in the mid-nineteenth century (Pyne 1982 and 1995; Courtwright 2011). While belowground NPP is important, it is difficult to estimate with historical data; long-term HANPP studies typically address only aboveground NPP (Krausmann et al. 2012; Fetzel et al. 2014; Gingrich et al. 2015). NPP_{act} measures actual vegetation produced in later years, revealing agriculture's impact. Unharvested Phytomass (UPH), a component of NPP_{act} , includes un-managed and un-harvested aboveground plant matter within farmyards and fields. Hedgerows, groves, riparian vegetation, weeds, and unused crop residues in the agro-ecosystem contained plant matter available to unmanaged food webs, from insects to birds to small mammals (Guzman

and Gonzalez de Molina 2015). UPH can provide energy to wild animals, potentially supporting biodiversity (Guzman Casado and Gonzalez de Molina 2009). Comparing NPP_{pot} with NPP_{act} and UPH reveals agriculture's impact on energy stored in phytomass, whether native plant or domesticated crop.

More pertinent to farmers and central to agriculture's economic goals are measures of gross and net farm productivity. Land Produce (LP) represents the energy produced by croplands, woodlands, and pastures. Livestock-Barnyard Produce (LBP) is the meat, milk, and other animal commodities produced on farms. Combined they constitute Total Produce (TP), the gross energy production of the managed system. But Total Produce is never entirely available to people. Farmers divert much of that production back into the farm system, as seed for next year's crop or as livestock feed and bedding. That crucial deduction from Total Produce, denoted here as Biomass Reused (BR), is energy that people must re-invest if the farm is to continue another year. The remainder, the farm's net energy production, is Final Produce (FP), goods available for local consumption or market sale. Agriculture's primary goal was not always to produce more energy. Some high-energy outputs, such as firewood, had low market value, while low-energy produce like fiber crops and meat had high market value. Energy processes in agro-ecosystems are not linear, with simple inputs and outputs, but looped, with energy inputs, internal cycling, and outputs (Tello et al. 2016).

Energy inputs (TIC) take two forms. Biomass Reused (BR) is energy derived from within the agro-ecosystem itself, and was always the largest input (9–27 GJ/ha). External Inputs (EI) include Labor (L) invested by the farm community plus energy carriers imported from outside the agro-ecosystem, such as machinery, fuel, synthetic chemicals, and imported livestock feed. Labor, which never exceeded 0.04 GJ/ha, was by far the smallest of these External Inputs. Imported energy derived from fossil fuels, on the other hand, rose in importance over time, from negligible in the nineteenth century to 4–12 GJ/ha at the end of the twentieth. The defining feature of the socio-ecological transition to industrial agriculture was increased inputs of fossil fuel energy embodied in imported tractors and trucks powered by internal combustion engines, plus their fuel. After the 1950s, chemical fertilizers, replete with embodied fossil fuel energy, constituted the largest imports on farms, while pesticides, electricity, and imported livestock feed contributed additional amounts. Irrigation was minimal in the counties evaluated here, but EI also includes the energy cost of lifting and distributing irrigation water. By the end of the twentieth century External Inputs of fossil fuels, chemical fertilizers, pesticides, and electricity delivered 15–30 percent of Total Inputs Consumed, but Biomass Reused still contributed over 70 percent. Tracing these energy flows across 140 years reveals the energy story of the Great Plains as it moved from a raw frontier to become a modern, industrial breadbasket to the world.

Variations of Great Plains Agriculture

Three Kansas counties provide case studies of dryland agriculture in the Great Plains (Figure 1). Prior to Euro-American settlement a semi-arid climate and landscape fire had created a grassland biome. Rainfall is highest (1000 mm/yr) on the eastern edge of the region, supporting tallgrass prairie. It declines toward the west, through mixed-grass prairie (650 mm/yr) to a western short-grass steppe (400 mm/yr) (Lauenroth and Burke 1995; Wishart

2007). Since average rainfall is marginal for crops, weather variability makes farming unreliable. Crops may do well eight years out of ten but fail in the other two. The counties profiled here depended on natural rainfall and practiced little irrigation. While this article focusses on human management of farm energy flows, in any given year rainfall may be more important to productivity than energy or soil fertility. Four time points capture key moments in agro-ecosystem energy transitions. In 1880 all three places were in the early stages of settlement by Euro-American farmers. Fifty years later, in 1930, Great Plains farm systems were fully developed, with all land converted to either cropland or fenced pasture for extensive grazing. That year captures the post-frontier plains just before the onset of the economic depression and devastating drought that characterized the “Dust Bowl” era (1932–1941) (Worster 1979; Hurt 1981). After recovering from the 1930s disaster, in 1954 the socio-ecological transition was in full swing, and by 1997 the region was home to a modern industrialized farm system.

Nemaha County, Kansas is on the wet eastern edge of the plains. Tallgrass and mixed-grass prairie covered most of the county, with low woodlands only along rivers. Nemaha averages 875 mm of precipitation annually, enough to support a variety of crops. Rich soils are deep and gently sloping with clay loam or silty clay loam textures (Kutnink et al. 1982). It was the first part of the interior grassland settled by Euro-Americans, beginning in the 1850s. Nemaha represents the prosperous, mixed-farming communities created during the mid-nineteenth century agricultural colonization of the Great Plains (Cunfer and Krausmann 2016). Only 200 km to the southwest, Chase County, Kansas strikes a marked contrast. Rainfall averages 815 mm, supporting a vigorous native vegetation of tallgrass and mixed-grass prairie (Neill 1974). The soils, however, are only a few centimeters thick and poor for agriculture. The thin-skinned limestone hills are unsuitable for the plow. Only in bottomland along rivers did settlers find soils deep enough for cropland. Instead, they exploited generous native grasses for cattle grazing. Since the 1850s Chase County has been ranching country, with land devoted to fattening beef cattle and only a small amount planted in feed crops and hay to see cattle through winter (Malin 1984). Farther west, settlement had barely begun in Decatur County, Kansas in 1880. Semi-arid climate averaged 525 mm of annual precipitation and supported short-grasses on 98 percent of the land. Soils are deep and level, with a silt loam texture (Hamilton et al. 1989; Cunfer and Krausmann 2009). Farmers eventually grew dryland wheat and drought-tolerant sorghum on half of the area and dedicated the other half to extensive, low-density cattle grazing. These three case studies represent characteristic types of Great Plains non-irrigated agriculture. Nemaha County’s rich soils and adequate rainfall supported prosperous mixed farming. Chase County’s adequate rainfall but poor soils allowed only extensive cattle ranching, while Decatur County’s good soils but low rainfall supported cereal farming and extensive cattle grazing.

Mixed Farming in Nemaha County, Kansas

Nemaha County’s tallgrass prairie generated 90 GJ/ha of aboveground biomass energy in its pre-settlement condition (NPP_{pot}). As Euro-Americans transformed that grassland into an agricultural mosaic they reduced plant productivity (NPP_{act}) significantly. By 1880, 25 years after initial settlement, energy productivity from the land was down 24 percent to 68 GJ/ha. Half a century later it had fallen to 56 GJ, just over half of its pre-settlement value. Then in

the mid-twentieth century a technological revolution—the socio-ecological transition—drove productivity higher. NPP_{act} rose to 71 GJ/ha in 1954 then to 120 by 1997. At the end of the twentieth century total plant energy production was 33 percent higher than under pre-settlement conditions. This progression, in two phases, reveals agriculture's basic environmental impact on natural systems.

Figure 2 presents energy profiles for Nemaha County in 1880 and 1930, indicating energy flows through the agro-ecosystem in GJ/ha, each arrow scaled to the size of its energy content. Land Produce (LP), the energy output of farmland, constituted the human-managed portion of NPP_{act} . Nemaha cropland, pastures, and woodland produced 22 GJ/ha of LP in 1880 and 30 in 1930. Livestock-Barnyard Produce (LBP) barely registered in 1880 at 0.5 GJ/ha, doubling to 1.0 in 1930. Another important portion of NPP_{act} went unused by the farm population as Unharvested Phytomass (UPH), remaining available for unmanaged biodiversity. UPH dropped during agricultural colonization, falling from 45 GJ/ha in 1880 to only 26 by 1930. In most years about half of NPP_{act} remained free for wild animals, though much less than under pre-settlement conditions.

Farm families could not consume or sell all of the farm system's Total Produce, however. First they had to re-invest a portion to secure farm continuity into the next year. Biomass Reused (BR) diverted some Land Produce into feed and forage for livestock, bedding straw, and seed for next spring's crop. In 1880 Biomass Reused consumed 18 GJ/ha, nearly 80 percent of Total Produce, climbing to 23 GJ in 1930. What remained, Final Produce (FP), was available for consumption or export to market. This energy flow, the primary objective of family labor and enterprise, was 5 GJ/ha in 1880 and 8 fifty years later in 1930. In those two years, from a gross farm productivity of 23–31 GJ/ha, farmers re-invested about 20 GJ as Biomass Reused, leaving net productivity (FP) of 5–8 GJ. External Inputs were modest at 4 GJ/ha in 1880 and 3 in 1930. They included farm machinery and fuel (plus the embodied energy of manufacture and transport) and a small amount of imported livestock feed. Labor (L), as demanding as it was for farm families, was less important in energetic terms, constituting only 0.04 GJ/ha. That low number demonstrates how effectively agriculture amplifies human work. In Nemaha County in 1930 a farmer returned 7.7 GJ/ha of Final Produce from a Labor investment of 0.04 GJ/ha, a ratio of 193:1. Pioneer farmers, through their sweat and ingenuity (and aided by generous liberal land policies), converted a tallgrass prairie into a prosperous farming community, one that required large energy reinvestments but sustained a comfortable lifestyle.

The next 75 years saw a second energy transformation that multiplied energy flows (Figure 3). The change resulted from an increase in External Inputs of inexpensive fossil fuel energy. EI doubled between 1930 and 1954, rising from 3 to 7 GJ/ha, and then nearly doubled again to 12 GJ by 1997. Most of that imported energy came as synthetic fertilizers that dramatically boosted crop yields, but it also included tractors, trucks, harvesters, and the fuel to power them, plus electricity and imported livestock feed. After 1930 EI quadrupled, sending a jolt of energy throughout the system. Farmers benefited by significantly raising marketable production (FP) and also increased Biomass Reused and Unharvested Phytomass, energy that did not make it into the monetary economy.

Not all energy flows changed in unison, however. While EI rose by 120 percent between 1930 and 1954, Final Produce increased by only 70 percent and Biomass Reused was flat. Unharvested Phytomass jumped from 26 to 35 GJ/ha. Then all energy flows rose sharply in the next 40 years. In 1997 EI was 12 GJ/ha and NPP_{act} jumped to 120 GJ/ha. Much of that, 57 GJ, was biomass harvested from farmland as LP, but UPH also rose, to 63 GJ/ha, nearly double 1954 levels. Unmanaged wildlife around Nemaha farms now had access to more energy than they had in over a century. Of the 58 GJ/ha of Total Produce, nearly half (27 GJ/ha) went into a much-increased Biomass Reused and the remainder to Final Produce (31 GJ/ha), which had increased by 240 percent. By pouring fossil fuel energy into their enterprises, farmers raised marketable production dramatically: FP quadrupled between 1930 and 1997.

Figure 3 reveals an interesting progression in the socio-ecological transition. Between 1930 and 1954 EI rose by 4 GJ/ha and FP kept pace, rising by 5 GJ. Then, between 1954 and 1997, EI climbed another 5 GJ, but this time FP went up by a remarkable 18 GJ/ha. As farmers mechanized in the early part of the socio-ecological transition, abandoning horses and mules for tractors, energy inputs rose and so did energy outputs. Then, in a second phase of transition, driven now by fertilizer, productivity exploded. Energy inputs climbed throughout the twentieth century, but the great gains in crop production happened only in its last several decades. Historians of agriculture have focussed on machinery as the defining technology of industrialized farming (Williams 1987; Fitzgerald 1991; Cunfer 2005). Most link agricultural modernization to the adoption of tractors, but synthetic fertilizers, with their high embedded energy content, were the most important driver of increased crop production, and that occurred a few decades later. Mechanization improved labor productivity, whereas synthetic fertilizers improved land productivity.

Extensive Cattle Ranching in Chase County, Kansas

With each move westward on the Great Plains farmers faced greater environmental challenges. Although Chase County is not far from Nemaha its energy profile looks quite different. Only slightly drier, but with poorer soils, all managed energy flows in Chase County were smaller. Rich grasslands supported extensive cattle grazing beginning in the 1850s, when Euro-Americans appropriated Native American land and replaced wild bison with livestock (Malin 1984; Courtwright 2011). Pre-settlement energy productivity was the same in both places (89–90 GJ/ha). In Chase County agricultural management reduced total productivity (NPP_{act}) over time, but only by 15 percent, to fluctuate between 74 and 79 GJ/ha between 1880 and 1954. In the late twentieth century ranchers pushed NPP_{act} back up to 91 GJ/ha, matching pre-settlement amounts. They accomplished this recovery through productivity gains on the 12 percent of land plowed for crops, mainly through fertilizer application. Chase County ranching had a smaller basic environmental impact than did Nemaha County farming.

In 1880 all Chase County energy flows except UPH were less than half those in Nemaha: energy inputs (EI) of 1 GJ/ha generated 10 GJ/ha of Land Produce, leaving 64 GJ of Unharvested Phytomass (Figure 4). Ranchers recirculated 90 percent of LP back into their livestock operations as Biomass Reused; indeed, they devoted nearly all of their small

amount of arable land to growing feed and forage crops to see cattle through winter. Final Produce of 2 GJ/ha left only a small amount of energy for export to markets, mainly in the form of live cattle shipped by rail to slaughterhouses in Kansas City or Chicago (Cronon 1991). That system continued with little change for over a century, bringing economic prosperity to a small population spread over a large area; population density was 3.5 people per km² compared to 9.8 in Nemaha County. In 1930 EI (2 GJ/ha) and UPH (65 GJ/ha) had hardly changed with LP (14 GJ/ha) and FP (4 GJ/ha) up slightly. In 1954 EI was still only 2 GJ/ha; LP (12 GJ/ha) and FP (2 GJ/ha) had fallen a bit. UPH remained the same at 67 GJ/ha. Ranchers still directed 90 percent of LP into Biomass Reused to feed cattle. In this extensive, low impact meat-producing economy the socio-ecological transition had not yet begun as late as the mid-1950s.

That finally changed in the second half of the twentieth century, but only modestly in energy terms. EI rose to 4 GJ/ha in 1997 and Land Produce jumped by 80 percent. Unharvested Phytomass was still flat at 69 GJ/ha. Ranchers drove livestock density from 18 animals/km² in 1954 up to 28 in 1997 by creating concentrated feed lots within extensive pastures. They also fed more produce to those cattle, raising Biomass Reused from 11 GJ/ha in 1954 to 19 in 1997. NPP_{act} rose by 15 percent to 91 GJ/ha in 1997, identical to its pre-settlement value. Final Produce doubled to reach 4 GJ/ha. This was a notable increase, but hardly the spectacular results created in the grain-growing regions. In Chase County EI tripled over 120 years, but only reached 4 GJ/ha in 1997, a level matched in Nemaha already in 1880. Final Produce dipped in the mid-twentieth century then doubled by 1997, but in that year it generated only an eighth of Nemaha's output. UPH remained stable through more than 150 years, above 70% of pre-settlement NPP. Biomass Reused rose after 1954, reaching a level 5 times that of FP. Natural conditions put strict limits on agro-ecosystem productivity in Chase County, and farm communities adapted by limiting cropland while fully exploiting pasture for cattle grazing (Cunfer and Krausmann 2016).

Dryland Cereal Production in Decatur County, Kansas

To the west, Decatur County faced a different environmental constraint. There soils were good but low rainfall was limiting. In this semi-arid shortgrass steppe, pre-settlement plant productivity (NPP_{pot}) was 47 GJ/ha, half that of Nemaha and Chase's tallgrass vegetation. The transition from native grassland to managed agro-ecosystem decreased productivity by half. NPP_{act} remained stable through the mid-twentieth century, then rose sharply by 1997 thanks to imported synthetic fertilizer. Between initial settlement and 1997, NPP_{act} rose from 47 to 68 GJ/ha, a 45 percent increase. Decatur County was on the western edge of frontier settlement in 1880, with very small energy flows; Final Produce was only 0.4 GJ/ha that year (Figure 6). During the next half century the county filled up, farmers plowed all arable land and grazed cattle on the rest. They planted wheat and sorghum, both of which became valuable export crops (Cunfer and Krausmann 2009). Between 1880 and 1930 Decatur's Unharvested Phytomass dropped from 23 to 18 GJ/ha. Land Produce, meanwhile, multiplied by 9 times, to 17 GJ/ha. Three quarters of LP went back into farms as Biomass Reused (13 GJ/ha), leaving 5 GJ/ha of Final Produce. By 1930 Decatur County's productivity did not yet match levels Nemaha County achieved 50 years earlier, a reminder of rainfall's powerful constraint.

In a now-familiar trend, external energy inputs rose between 1930 and 1954, to 6 GJ/ha, while Final Produce remained virtually the same (Figure 7). Here again, early investments in fossil fuel energy had little effect on FP or BR. Between 1954 and 1997, however, the socio-ecological transition brought dramatic results through the application of synthetic fertilizer. The same 6 GJ/ha of EI now pushed internal energy flows and outputs upward along with it. Land Produce doubled to 33 GJ/ha. Biomass Reused captured 17 of those GJ, leaving 16 GJ/ha as Final Produce. Unharvested Phytomass rose, up 100 percent to 35 GJ/ha. This highly industrialized farm system produced a lot of marketable grain and also left for wildlife three quarters as much biomass as under pre-settlement conditions. In 1997 Decatur County's managed energy flows were a bit over half the size of those in Nemaha, but larger than in Chase County. These comparisons reveal the relative impact on productivity of soil quality and rainfall differentials.

Conclusion

Great Plains agro-ecosystems underwent two energy transformations. *Agricultural colonization* began in the eastern plains in the 1850s, in the western plains in the 1880s, and concluded everywhere by the 1920s. Through the first 75 years nearly all land in the region became either cropland or grazed pasture (Cunfer 2005). In the process, farmers reduced plant productivity compared to pre-settlement conditions. Then, over the next 75 years, a second energy transformation, the *socio-ecological transition*, multiplied plant productivity again. Today the two grain-growing counties produce 33 to 45 percent more energy than they did prior to settlement; plant production in ranching county is virtually identical to that in c.1850. The socio-ecological transition depended on fossil fuel energy in a variety of forms, but most prominently in synthetic fertilizers. Tractors and trucks transformed farm family lifestyles and required energy imports, but they only modestly raised land productivity. In the mid-twentieth century biomass energy outputs lagged behind climbing fossil fuel energy inputs. Then, when fertilizer took off in the 1950s, productivity rose much faster. Climbing NPP_{act} came from Land Produce, which rose by multiples, and also from Unharvested Phytomass. The latter rose modestly in grazing regions where it had always been high and dramatically in grain-growing areas. Landscape conversion into agro-ecosystems during agricultural colonization increased harvested portions of NPP_{act} and decreased unharvested portions. The socio-ecological transition boosted all energy pathways.

Higher rainfall in the eastern plains allowed farmers to benefit more and earlier from external energy investments. In 1930 Nemaha farmers applied 1 kg of fertilizer per hectare of cropland, compared to 1/3 kg in Chase County and none in Decatur (U.S. Census Bureau 1930). In 1954 farmers in wetter Nemaha and Chase Counties applied 45 and 39 kg/ha, respectively, while those in dry Decatur County had not yet reached 1 kg (U.S. Census Bureau 1954). By 1997 fertilizer applications had leveled off in Chase County (43 kg/ha), risen substantially in Decatur County (59 kg) and tripled in Nemaha County (139 kg). By the late twentieth century all Kansas farmers employed energy-rich fertilizer to boost crop yields, but more so in eastern Kansas, where rainfall was sufficient for nutrient-hungry corn. In the dry western part of the state farmers grew wheat and sorghum, which need less water and fewer soil nutrients. Nemaha County farmers began the socio-ecological transition

decades earlier and reaped greater productivity increases than did grain farmers in Decatur County.

These results add nuance to previous studies of NPP_{act} in the Great Plains (Lauenroth 1979; Bradford et al. 2005) and reveal an agro-ecological context rarely addressed in HANPP studies. Assessing the entirety of the U.S. Great Plains, Bradford et al. (2005) estimated that cultivation raised aboveground NPP by 26 percent, somewhat lower than the 33 to 45 percent increase estimated here. Most of that gain came from corn cultivation, and a smaller part from wheat and sorghum, with irrigation and fertilizer applications as the primary drivers of increasing NPP. Without contradicting those region-wide results, the case studies explored here highlight internal energy loops and expose the energy constraints imposed by climate and soil. Human Appropriation of Net Primary Production studies have addressed global scales (Imhoff et al. 2004; Haberl et al. 2007; Krausmann et al. 2009; Haberl et al. 2009; Erb et al. 2009a; Erb et al. 2009b; Krausmann et al. 2013) or European nations (Haberl et al. 2005; Musel 2009; Schwartzlmuller 2009; Kohlheb and Krausmann 2009; Vackar and Orlitova 2011; Gingrich et al. 2015) but not the New World. Long-term HANPP studies in those regions begin centuries after agricultural colonization and focus on the twentieth century's socio-ecological transition. Other HANPP studies address the Philippines (Kastner 2009), South Africa (Niedertscheider et al. 2012), New Zealand (Fetzel et al. 2014), and Canada's Nova Scotia (O'Neill et al. 2007). Thus far scholars have neglected the Americas, which were characterized by Euro-American colonization, low population densities, and export-focussed agro-ecosystems. There are no HANPP studies agricultural frontiers (except for New Zealand, where settlers converted forest to sheep pasture but grew few crops). Most HANPP research assumes that native vegetation was forest, rather than grassland, with important implications for NPP_{pot} . The energy consequences of clearing forest for farmland are different from those in native grassland. For example, Gingrich et al. (2015) found that the socio-ecological transition led to less cropland, forest regrowth, and NPP_{act} values around 10 percent higher than NPP_{pot} . The present study shows that NPP gains from the socio-ecological transition may be even higher in grasslands.

Comparative internal energy flows also reveal interesting patterns. All farms and ranches in the Great Plains required reinvestment of Biomass Reused. That was true during the late nineteenth and early twentieth centuries, but even more so after the socio-ecological transition. In both ranching and grain-growing regions, rising EI did not substitute for Biomass Reused, but rather drove it higher alongside Final Produce. Likewise with Unharvested Phytomass. Increasing flows of BR fed more livestock for meat production, but LBP remained small compared to other energy flows, never climbing higher than 1 GJ/ha. The conversion from livestock feed (BR) to meat (LBP) is inefficient, with large energy losses via waste heat. Converting fossil fuels (EI) into feed crops (BR) and then into meat (LBP) is even less efficient. Increased EI did not diminish BR or UPH on their way to boosting FP. Instead EI raised all three energy flows. The flush of new energy through agro-ecosystems affected all aspects of farms, including domesticated livestock, market exports, and some wildlife.

While the socio-ecological transition brought changes everywhere in the Great Plains, there were regional variations. Wetter, eastern areas began importing fossil fuel energy earlier than drier areas, and they saw larger returns. Regions with poor soils also increased energy imports, but at lower levels and later than places with abundant cropland. In the eastern plains farmers invested in tractors in the 1910s and applied synthetic fertilizer in the 1920s (Kansas State Board of Agriculture 1915; U.S. Census Bureau 1930). By the 1930s farmers in the dry western regions transitioned to tractors, but they adopted fertilizer only after the 1950s, and even then applied it at a third the rate of those to the east. In the Kansas's bluestem pastures, where soils were thin, ranchers used fossil fuel energy to increase feed crops, but energy imports and exports remained low. Rainfall and soils were limiting factors, even in an era of cheap, abundant fossil fuel energy.

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Appendix: Sources and Methods

Historical energy profiles depend on aggregate county-level data from agricultural censuses (U.S. Bureau of the Census 1880, 1930, 1954, 1997) that report crop area and production, number of livestock and machinery, and amount of irrigation and fertilizer use. With harvest index values and energy conversion factors it is possible to convert reported harvests into energy equivalents. For example, according to Guzman et al. (2014), heritage varieties of corn had a harvest index of 1.22 kg of residues for every 1 kg of grain produced. The grain had a gross fresh weight energy content of 14.44 MJ/kg and the residues 15.48 MJ/kg. The 1880 census reports that farmers in Nemaha County harvested 2.1 million bushels of corn that year. By converting to kilograms, multiplying by the energy coefficient, and separating grain from residues, it is possible to estimate that land planted in corn produced 774 GJ of energy in grain and another 892 GJ in residues. Similar calculations for all crops, plus grazed native grass, hay, and firewood, produce an estimate of Land Produce—all the energy flowing from croplands, pastures, and woodlands.

With census data about the number of horses, mules, swine, poultry, and milk and beef cows, it is possible to estimate energy flows through livestock. A feed balance approach relies on scientific literature about livestock feed, forage, and bedding requirements, based on monthly variations in draft animal work loads, fattening schedules, and milk production. It is assumed that farmers met livestock needs first from local crop production. Feed shortfalls must have been imported from outside the county. These flows are converted to their intrinsic energy equivalencies based on gross calorific values, measured in joules.

The energy content of native pasture comes from grass productivity reported in modern soil surveys (Neill 1974; Hamilton et al. 1979; Kutnink et al. 1982). Per-area calculations for the entire county determine NPP_{pot} , while the same productivity rates applied to total pasture area reported in censuses estimate the contribution of grazing land to LP.

External Inputs are estimated using embodied energy values. Labor is estimated by applying a standard annual energy exertion of 2 GJ/person/year to the number of working-age men and women on farms (Cunfer and Krausmann 2016). From 1930 onward, the census reports the number of tractors in each county. It is possible to estimate the amount of energy expended to produce the steel and rubber components of a new tractor (Audsley et al. 1997), amortized over a 35-year lifespan, combined with the embodied energy content of diesel fuel to run it for a year. Multiplying those factors by the number of tractors, trucks, and harvesters in a county provides an estimate of the machinery and fuel energy deployed in the agro-ecosystem (Cleveland 1995; Miranowski 2005).

The census reports the dollar value of fertilizers and lime applied in 1880, which can be used to estimate application rates (Parker et al. 1946). In 1930 and 1954 the census reported the total quantity of fertilizers applied, but without specifying the proportion of Nitrogen, Phosphorus, and Potassium (N-P-K). For those years proportional N-P-K rates, and the energy embodied in them, are estimated based on national-level data and regionally typical application patterns (U.S. Bureau of the Census 1960). In 1997 county-level fertilizer application data are available from IPNI (2012). Pesticide use is estimated as zero in 1880 and 1930. Pesticide use for 1954 is based on 1958 national-scale application rates on three major pesticide-receiving crops: cotton, corn, and potatoes (Osteen and Szmedra 1989; Strickler and Hinson 1962). Thelin and Stone (2013) provide county-level pesticide use for 1997. Electricity use estimates for 1954 come from detailed information about irrigation pumping needs (Sloggett 1985; Kansas Geological Survey 2002) plus a standard per-farm electricity consumption rate provided by Davis (1956). Electricity use in 1997 comes from the census and the U.S. Energy Information Administration (2013).

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Fig. 1.
Case study counties in Kansas, with agro-ecological zones (Malin 1944)

Fig. 2.
Agro-ecosystem energy profile of Nemaha County, Kansas, 1880 and 1930

Fig. 3.
Agro-ecosystem energy profile of Nemaha County, Kansas, 1954 and 1997

Fig. 4.
Agro-ecosystem energy profile of Chase County, Kansas, 1880 and 1930

Fig. 5.
Agro-ecosystem energy profile of Chase County, Kansas, 1954 and 1997

Fig. 6.
Agro-ecosystem energy profile of Decatur County, Kansas, 1880 and 1930

Fig. 7.
Agro-ecosystem energy profile of Decatur County, Kansas, 1954 and 1997

Table 1

Energy flows (GJ/ha) in three Kansas counties, 1880, 1930, 1954, and 1997.

Nemaha County, Kansas		Presettlement	1880	1930	1954	1997
Actual Net Primary Production	NPP _{act}	89.6	67.5	55.7	71.0	120.5
Land Produce	LP		22.1	29.9	35.8	57.0
Livestock-Barnyard Produce	LBP		0.5	1.0	0.6	0.9
Total Produce	TP		22.5	30.9	36.4	58.0
Biomass Reused	BR		17.5	23.2	23.3	27.4
Final Produce	FP		5.0	7.7	13.1	30.5
Unharvested Phytomass	UPH		45.5	25.9	35.2	63.4
Labor	L		0.0	0.0	0.0	0.0
Agroecosystem Societal Inputs	ASI		3.9	3.2	7.1	11.8
External Inputs	EI		3.9	3.2	7.1	11.8
Total Inputs Consumed	TIC		21.4	26.4	30.3	39.2
Final EROI	FEROI		0.2	0.3	0.4	0.8
Internal Final EROI	IFEROI		0.3	0.3	0.6	1.1
External Final EROI	EFEROI		1.3	2.4	1.9	2.6
NPPact EROI	NPPEROI		3.2	2.1	2.3	3.1
Area (ha)			187,957	185,443	183,630	186,239
Percent cropland			24.3	59.7	59.4	53.9
Livestock Density (LU500/km ²)			27.3	33.6	33.5	36.9
Population Density (cap/km ²)			6.6	9.8	7.8	5.8
Precipitation (mm)		875 (avg)	NA	762	851	838
Chase County, Kansas		Presettlement	1880	1930	1954	1997
Actual Net Primary Production	NPP _{act}	88.6	74.1	79.1	79.1	90.8
Land Produce	LP		10.5	13.9	12.3	22.3
Livestock-Barnyard Produce	LBP		0.2	0.3	0.2	0.4
Total Produce	TP		10.7	14.3	12.6	22.7
Biomass Reused	BR		8.6	10.2	11.0	18.5
Final Produce	FP		2.1	4.1	1.6	4.2
Unharvested Phytomass	UPH		63.7	65.1	66.7	68.6

Nemaha County, Kansas		Presettlement	1880	1930	1954	1997
Labor	L		0.0	0.0	0.0	0.0
Agroecosystem Societal Inputs	ASI		1.4	2.0	2.5	4.2
External Inputs	EI		1.5	2.0	2.5	4.2
Total Inputs Consumed	TIC		10.1	12.1	13.5	22.7
	Final EROI	FEROI	0.2	0.3	0.1	0.2
	Internal Final EROI	IFEROI	0.2	0.4	0.1	0.2
	External Final EROI	EFEROI	1.4	2.1	0.6	1.0
	NPPact EROI	NPPEROI	7.4	6.5	5.9	4.0
Area (ha)			207,257	199,170	199,656	200,967
Percent cropland			8.4	18.5	15.1	12.1
Livestock Density (LU/500/km ²)			12.9	16.0	17.5	28.0
Population Density (cap/km ²)			2.9	3.5	2.4	1.5
Precipitation (mm)		815 (avg)	NA	749	573	1001
Decatur County, Kansas		Presettlement	1880	1930	1954	1997
Actual Net Primary Production	NPP _{act}	46.9	24.5	35.4	33.8	67.5
Land Produce	LP		1.8	17.0	17.1	32.7
Livestock-Barnyard Produce	LBP		0.0	0.4	0.2	0.3
Total Produce	TP		1.8	17.4	17.4	33.0
Biomass Reused	BR		1.4	12.5	11.6	16.9
Final Produce	FP		0.4	4.9	5.8	16.1
Unharvested Phytomass	UPH		22.7	18.3	16.6	34.9
Labor	L		0.0	0.0	0.0	0.0
Agroecosystem Societal Inputs	ASI		0.3	1.3	5.6	6.0
External Inputs	EI		0.3	1.3	5.6	6.0
Total Inputs Consumed	TIC		1.7	13.8	17.2	22.8
	Final EROI	FEROI	0.2	0.4	0.3	0.7
	Internal Final EROI	IFEROI	0.3	0.4	0.5	1.0
	External Final EROI	EFEROI	1.2	3.8	1.0	2.7
	NPPact EROI	NPPEROI	14.1	2.6	2.0	3.0
Area (ha)			225,108	230,768	232,840	231,440
Percent cropland			3.1	55.3	56.0	50.9

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Nemaha County, Kansas	Presettlement	1880	1930	1954	1997
Livestock Density (LU500/km ²)		2.3	16.1	12.8	22.1
Population Density (cap/km ²)		1.9	3.8	2.7	1.5
Precipitation (mm)	525 (avg)	NA	381	746	493