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Protecting and Valuing Wild Native Plant Species Genetics During Domestication

Steven I. Apfelbaum[1]* and John Elstrott, PhD[2]

[1]Senior Ecologist, Applied Ecological Institute, Inc, N673 Mill Rd.Juda, WI 53550
[2]Chairman, The Climate Food Company, LLC, Boulder, CO

***Correspondence:** Steven I. Apfelbaum, Applied Ecological Institute, Inc, 673 Mill Rd, Juda, WI 53550, 608-201-9375 E-mail: steve@aeinstitute.org

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1. Abstract

We ask the following questions to inform how native perennial plant species might integrate with mainstream agriculture:

1. Can native plant species contribute to a future perennialized agriculture, without compromising the genetic diversity of wild plant species, populations, and wild habitats?
2. How can domestication of native plant species grown for food avoid our existing agricultural system pitfalls of simplified, narrowed genetics, and reduced resilience?
3. Can inclusion of native plant species in a future food supply help internalize economic externalities in the existing human food supply chains, increase nutrition, and help improve the environment and human health?

This paper explores a regenerative agricultural future that could integrate native perennial plant species as crops, or in rotations to improve soil health, biodiversity, and water resiliency. And, how a perennial agriculture could operationalize and create lower cost accountability to assure food supply certifications and values for farmers.

2. Introduction

Human cultivation of former wild plants has been the source of all plants we eat. The domestication of crop plant species has been a process of human selection that began over ten thousand years ago [1,2]. This process has focused primarily on annual plants, often self-compatible species grown from seed each year. Recently, perennial plants have become of interest to address climate resilience, food supply chain risk and demand from an increased population. Most native wild perennial plants rely on wind or insect cross pollination (outcrossing) or clonal (vegetative spread) growth which are two big differences compared to domesticated annual plants (e.g., grain crops) which have experienced extensively changed genetic variation compared to their wild progenitors and created the genetic basis of domestication for agriculturally important traits.

This story and process of domestication has been synonymous with human experimentation, discovery, and learning and co-evolved with human evolution. This journey has in recent times transitioned to a rigorous, competitive, and lucrative enterprise alongside a civilization that now depends on the success of this enterprise, and increasingly on global, not local markets and financing. However, this has narrowed and focused genetics and production of single crop monocultures, and proprietary ownership of patented cultivars. This has had profound consequences. This has contributed to very few crop plants comprising the global food supply and narrowed yield-biased genetics of those species, and a range of unanticipated consequences/impacts, including reduced food security, declining nutritional density, and crops dependent on fertilizer, herbicide, and pesticides for achieving high yields and consumer alluring "showier" grain, fruit, and vegetables [3]. Secondary consequences include declining ecosystem services including reduced pollinator services, air and water cleansing, soil health and productivity, flood water management, among others [4,5,6].

Agriculture is changing rapidly to respond to changing growing conditions, diseases, drought, and storm intensification. Estimates of the risks of maintaining the status quo food supply systems have predicted unfathomable economic, health loss and suffering, and escalating decline of land health and productivity, crop loss and farm business failures. Agencies, financial institutions, insurance, and re-insurance organizations the world over are beginning to realize we have compromised our future, not meeting the needs of the present or future, and that a different approach to agriculture; a regenerative future is essential [7,8,9].

Considering our history, can food systems take another path? Can balance, including introducing long lived durable wild native species, and conserving their genetics and the health of ecosystems and habitats of their origin be a foundation for a regenerative future food supply. Can this strategy yield the following positive externalities: re-grow healthy soils and re-grow water supplies, while maintaining native wild stocks, produce more healthy nutrient dense food, livestock, and overall healthy land? This approach asks us to consider a future primarily focused on balance; and secondarily on yield, consumer allure, and economic returns. It also suggests that using the resilience of native plants may be critical to our success in mitigating climate and future food supply risks. Accounting for the negative economic externalities under existing agricultural enterprises would be a novel and necessary shift in agriculture.

Such a shift needs to occur rapidly, but presently is not achievable on a pedictable timeline. Entrenched large company economic interests, agricultural policies, subsides, lack of political will, and a need for increased consumer food education are presently obstacles to the changes required in the global food system. Perhaps taking a parallel path, that springboards from existing successful production technologies, but is not burdened by the existing agricultural system is even essential. We evaluate how native perennial wild food plants can be introduced into our food systems and our diet.

Recently, a number of lost "grain" crops (ancient and wild native plant foodstuffs) have successfully re-entered the modern food supply chain; Quinoa, Amaranth, Eincorn wheat, and Triticale are several examples. New and ancient fruit have also entered: Sumo citrus, Breadfruit, Monk fruit, Hardy kiwi and many others. Most have experienced moderate to rapid success in the marketplace and our modern diet, expedited by chefs, food companies, and consumers. It is clear the market place is ready and wanting food diversity [10].

How can native wild plants contribute to the human and livestock food supply chains? How can scaling a perennial native-species-based agricultural system contribute to the future needs outlined above, while simultaneously protecting the genetic diversity of the wild plant species used in future agriculture enterprises?

Cultivation and domestication have molded former wild plants to meet our needs by genetic selection or hybridization (or more recent direct gene modification) to make those plants broadly adaptable across diverse growing conditions of soil types, and meteorological regions. This has occurred using conventional agricultural procedures, planting, cultivation, harvesting, cleaning, storage and other handling equipment and requirements. Varieties and cultivars with narrowed growing condition limits, increased fertility needs, and herbicides to compensate for their inability to compete with other plants have become prevalent. If a native plant's innate capacity to compete and prosper under conditions and pest insect and disease burdens, whether perennial or annual crops, could be part of our food supplies how would this change the face of agriculture? Could we start with species most like crop plants and take advantage of and protect its genetic diversity and the broader adaptability under changing conditions (e.g., storm intensification, drought cycles and severity), to achieve improved crop resiliency?

For 40 years harvested native wild plant seeds have been used to produce large volumes of native plant seeds for ecological restoration, mined land reclamation and many other types of projects in the USA [11]. Approximately 800 native plant species of North American's ecosystems are being protected in one Wisconsin, USA "seed bank" which includes > 30,000 accessions, each from a specific collection site. This "mother stock" annually produces tens of thousands of pounds of seed, and millions of potted plants needed for ecosystem restoration projects.

Over this same period, the original seed collection locations have been eliminated by land development and agricultural conversions. In short, this Wisconsin seed-bank, retains a primary native plant species genetic library from midwestern USA ecosystems. Priceless may be the best word to explain the value of this resource to the future of humanity. Habitats and plant species well-documented declines coincide with that of wildife such as Monarch butterflies as milkweed host plants and their habitat are lost. We feel responsibility to protect and steward the genetics of these plant species wisely into the future and believe the value for human food and to producer farmers is one important way to fulfill this protection.

During the same period of habitat and species decline, there has been an increased demand to rekindle historic uses of these native plants. Many species have a long history of Native American-uses as food and medicines. But this use has largely been forgotten or resides in brief summary forms in the ethnobotanical literature [12]. During forty-year's working with native species, protecting and benefically reusing the diverse genome for each of the species has been the goal. The goal now is to more broadly explore how the same collections can be used to stimulate a regenerative and sustainable agricultural future.

Let's ask what value and role can native wild plants provide us:

1. If native plants become a potential new food source for humans and animals, is protecting their habitats a conservation tool of increased importance for the future? Or, stated differently, can native plant species contribute to a future perennialized agriculture, without compromising the genetic diversity of wild plant species, populations, and habitats?
2. Is there validity to using native perenial plant crops (e.g. Virginia and Canada Wild Rye Grass grain) for human food? Or, stated differently, can production and delivery of native perennial plant foods be cost competitive with conventional crop production?
3. Can industry take account of existing positive economic externalities by creatively addressing modern food production systems regulatory risks by introducing the multiple-benefits of growing/producing native perennial plants such as native grains for food? Or, stated differently, can native crops cost less than conventional crops?
4. If native plants become a potential new food source for humans and animals, is protecting their habitats a conservation tool of increased importance for the future?

3. Methods

Conservation biology (landscape and habitat) principles [13] and conservation genetics principles [14] are used to explore a framework for protecting native plant genetic resources in the context of their production for human food. Potential concerns, and strategies for genetics preservation were foundations and are summarized as a basis for consideration.

We examined the nutritional basis for several example native perennial grains by comparing an abbreviated summary of the key nutrtional content with conventional grain crops. Nutritional data is certified laboratory analysis results of two example species [15], for fats, protein, carbohydrates, fiber, fat, ash, and calories.

We examine the economics of conventional grain and native plant grain production, using all-in costs for seed, farmfield soil preparation, planting, cultivation and chemical weed management(e.g. using herbicides, fungicides, insecticides, etc), crop harvesting, and grain processing (e.g. drying and cleaning) for the native perennial plant crops. We use two example wild native grass (grain) species (*Elymus virginicus* and *E. canadensis*) and compare full delivery production costs with the published costs for conventional grains and have summarized the costs on a weight equilibrated basis (e.g. $/lb of protein). To compare the costs for an annual grain crop with the perennial wild rye grasses which are planted once every 7-10 years, both were summarized over a ten year cycle. We then annualized average fully loaded costs using USDA published custom farming costs for the specific practices used to grow wild rye and corn production in Green County, WI. We used private cost records for Rye from ~ 20 years of production records.

To estimate externalized costs for both grain production systems, we compared GHG emissions and soil organic carbon stocks dynamics. Soil organic carbon data from paired, low disturbance cropped and conventionally cropped wheat/pulse fields in Washington State was used for this projection and used repeat sampling of farm fields the 8th year after baseline sampling to measure changes in organic soil carbon stocks. This used soil sampling to 1 meter depth and followed approved standard carbon market methods under VERRA VM0021 [16], to design and collect stratified random core samples (n=800) which were analyzed by pedological strata for total, inorganic and organic carbon and bulk density by strata in low disturbance cropped (one pass no tilled land) and adjacent conventional tilled acreages in the Palouse agroecosystem of Washington State.

We created a high level Life Cycle Analysis summary of conventional farmed wheat/corn and perennial wild rye grain production to further understand externalities. This is a conservative estimate that used USDA conversion GHG and carbon stock changes [17,18] in converting a row crop field to perennial grasslands, elimination of fertilizers, which we used for estimating native perennial wild grain crop soil carbon stock relations over time. This conservative estimate considers identical crop production using no till seeding, but eliminates the annual replanting, fertilizer, irrigation, herbcide used in only corn producton, and considers for corn and Wild Rye this over the ten years in a wild rye crop production cycle.

4. Results

1. **If native plants become a potential new food source, is protecting their habitats a conservation tool of increased importance for the future?** Or, stated differently, can native plant species contribute to a future perennialized agriculture, without compromising the genetic diversity of wild plant species, populations, and habitats?

It appears that the principles of Conservation biology [13[and conservation genetics [14] provide a framework for growing and conserving native plant genetic resources (**Table 1**). Compared to annual crop plants, wild perennial plants typically have more genetic variation, and have longer life cycles, which combined appear to provide less vulnerability to genetic bottlenecks compared to cultivated crops and can benefit from wild-crop-wild gene flow, to maintain genetic and phenotypic variation. This suggests a strong alignment between conservation biology and conservation genetic principles. If so, this could simplify the domestication process for perennial wild native plants, with the following guiding principles or goals:

A. Protection of wild and domesticated plant genetic diversity by protecting founder habitats and their biodiversity.

Table 1: Consolidated conservation biology and conservation genetics principles that may be critcial to the domestication of native wild perennial plant species.

Conservation Biology Genetic Principles	Biome	Parcel	Species/habitat	Seed
Gene Flow	Maintain remnant populations in a mosaic of native ecosystems to maintain wild populations as "mother stock" for re-introduction of trait diversity over time	Maintain connections to native populations to support gene flow and reduce risk of isolation or gene skew	Create conservation plantings within and around the production fields with pollinator habitat, and with native wild populations of the crop species	Maintain all phenotypic expressions of seed sizes, shapes and ensure that in seed production, handling, harvesting, cleaning, and, storage and ensure all can be used in plantings
Genomic diversity	Include representative populations from biome to create inclusive genomic expressions for the species	Create plantings representing the full diversity of genomic expressions	Create conservation plantings within and around the production fields with pollinator habitat, and with native wild populations of the crop species	Maintain all phenotypic expressions of seed sizes, shapes and ensure that in seed production, handling, harvesting, cleaning, and storage and ensure all can be used in plantings
Genetic Selection	Represent appropriate numbers and geographic distrubitions of the targeted crop species. For polygenomic species, represent multiple geographic regions in the mother stock collections	Harvest and retain all grain from a crop field and reuse this in future crop production		Ensure seed cleaning reduces non-targeted seeds, and chaff, but Minimize seed size sorting use, and maintain a seed storage facility % humidy summed with the temperature (degrees F) > 100 to best ensure viability of all seed phenotypes.
Genetic Bottleneck	Addressed by above	Addrsessed by above	Addressed by above	Addressed by above
Inbreeding Suppression	"	"	"	"

B. Protect founder population and domesticated crop wild to crop and crop to wild gene flow at the individual, population, metapopulation, and geographic distribution for each species brought under domestication.

C. Integrate restored and protected habitat with wild populations of the domesticated species in the agricultural landscape for multiple benefits (e.g., genetic maintenance, pollinator habitat, nutrient beneficial reuse and capture, pest insect control using native insect diversity.

D. Recognition, acknowledgement, and affirmation that managing any part of the ecosystem affects the ecosystem.

E. Aligning ecosystem restoration, management, and protection with that of agricultural landscape restoration, management, and protection; the management of land comes together under one ethic, one framework of operations.

F. Truly, achieving regenerative agricultural to supplement (if not supplant or supersede) conventional industrial and even organic agriculture.

These conservation biology and conservation genetics principles seem to strongly support regenerative agricultural and can provide multiple benefits from crop perennation (**Table 1).**

Translating the conservation biology and genetics framework into action steps, is required to achieve the principles to protect, conserve, and restore native seed plant populations, habitats, and remnants and link these with agricultural crop production uses of the targeted plant species. The following "strawman" draft and preliminary steps might be to foundational how to apply this framework:

1. Identify and map native plant populations, habitats and remnants of targeted native plant (a targeted native plant is the specie/or species for which domestication) is sought.
2. Characterize(summarize) the overall diversity of assoicated plants, pollinators, soil microbial life present in the ecosystem remnant settings where the native plant populations grow.
3. Map the historic distributions of the targeted native plant species and their habitats across their historic geographic distrubutional range, existing range, and local settings around the anticipated farm operation lands.
4. Attempt to replicate the gene-flow patterns afforded by wind, habitat connectivity, and spatial-habitat proportions of landscape patterns based on the relationships between soils and hydrology settings in known remnant habitats/population centers, and the same conditions/patterns over existing farmlands devoid of targeted species and their historic habitat.
5. Integrate habitat restoration within the agricultural landscape complex to contribute to the connectivity, gene mobility patterns, and landscape patterns of functional centers of origin for pollen and insect pollinators.
6. Recognize the value of native plant species and their genetics in any decision-making.
7. Any use of native plants should always focus on protecting the genetic diversity of native plants and the community of which they are a part.
8. Create a plan to ensure that the protection of the native plant genetic diversity is foundational to any commercialization program for native plant-use in agriculture.
9. Measure and maintain genomic diveristy using laboratory techniques to quantitatively characterize genetic diversity of the targeted plant species.
10. Measure wild to crop and crop to wild gene flow to represent the relationships between land, time and localized species adapatiations between wild and crop land populations of the targeted plant species.

2. **Is there validity to using native perennial plant crops (Virginia and Canada Wild Rye Grass grain) for human food?** Can the production and delivery into food supply chains of native perennial plant foods be cost competitive with conventional crop production?

New products using native perennial Virginia and Canada wild Rye grasses (*Elymus virginicus and E. canadensis)* are now being explored for use in human food [19]. For these grasses, several decades of production records and well documented costs, and a nutritional analysis have been completed for products and as ingredients for human consumption.

The production cycle involves direct no-till drilling of the seed with known seeding density per row, and row spacing, and has the potential to involve no fertilizer, herbicide, fungicide, irrigation, or cultivation needs. The plants establish rapidly and endure for 7-10 years of a grain production cycle. Deep root systems support cation mobilization, and associated significant increased microbial biomass associated with the heavy fibrous root system that supports myccorhizal associates such as nitrogen fixing soil bacteria, among other groups of fungi, bacteria and other soil life.These species are several of many targeted for food supply chains [15].

Comparisons of food nutrition constituents in native plant grain verse wheat have demonstrated flour made from native wild rye grain has significantly lower carbohydrates, starch, fat, and have significantly higher insoluable and soluable fiber, and because of the higher fat found in whole wheat grain, and native grains have moderately less calories (**Table 2**). Notably, wild rye protein levels have ranged between 22-28%, which can be over twice that of most wheat varieties, [15].

3. **Can industry account for existing economic externalities by introducing the multiple-benefits of growing/producing native perennial plants such as native grains for food?** Or, stated differently, can native crops cost less than conventional crops?

We asked, "Can native plant crops help address negative economic externalities in the existing human food supply chains, provide increased nutrition and improved human health? Comparing native plant grains, costs of production with that of wheat suggests with native rye grasses the production costs are not likely to include costs for tillage, fertilizer, herbicides, pesticides, irrigation, and fungicide use; or, if any of these are necessary, this would occur only during the initial planting year of the multi-year crop cycle. So too is the cost of patented proprietary seeds avoided. Using the annualized averages for conventional grains, by normalizing 'wild rye grains' and annual grain average protein content (**Table 2**), this analysis suggests Wild rye to have significantly lower costs per lb. of protein produced, (**Table 3).** Despite the lower yields of the native grains per acre, this result occurs in part because the planting of native grains occurs only once every 7-10 years, compared to yearly plantings and the other costs of conventional grains. Thus, because of eliminated annual production input costs, the native grain yields are significantly lower cost per pound(unit) of protein/acre.

Based on this analysis, Wild Rye grain production has the lowest cost and cost/unit of protein produced per acre annually. This evidense suggests that Wild rye production is more efficient which may be further strenghtened if unaccounted negative economic externalites such as cost of damages to biodiversity, water supply impacts, erosion and sediment impacts in our nations waterways, and water quality impacts were compared and considered between conventional row crop agriculture grain production and native perennial crop impacts, including impacts to human health [20].

Table 2: Comparisons of primary food product label nutritional constituents for Virginia and Canada Wild Rye grain compared to Wheat. Comparison is based on % of 100 gram at ~12.6 % moisture, rather than bone-dry weight samples.

Constituent	Nutrients per 100 g (% dry weight)		
	Wild Rye Grasses Grain		Whole Wheat Grain
	E.virginicus	E.canadensis	Literature
Carbohydrate	42.09 (64.7%)	49.39 (63.5%)	61.7[b]
Starch	37.4	45.2	63.8, 77.52
			46.7
Fiber (Total)	26.5	25.9	16.4
Insoluable DF	20.5	22.4	16.87
Soluable DF	6.1	3.5	1.69[b]
Protein	22.1	23.5	10.0-15.4, 11.4
			20.0
			20.8[b]
Fat	2.69	2.49	3.21, 2.18
Ash	2.64	2.18	2.64, 2.03
Moisture	11.3	11.6	12.653%
Total Calories (per 100g)	346.0	345.0	
Calories from fat	6.0	5.0	

5. Evaluation of Soil Carbon and GHG Emissions Externalities.

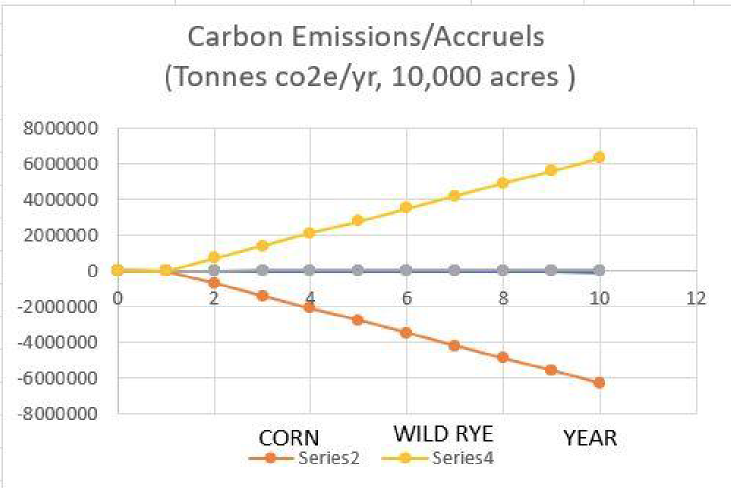
One externalized cost, the degradation of soil organic carbon under conventional agricultural grain production, annually emits substantial ghg emissions from soil tillage and the use of caustic anahydrous ammonium fertilizer; both contribute to the deterioration of soil organic carbon. Tillage and this fertilizer hasten the decomposition of organic carbon through bacterial decomposition [21]. The emerging carbon marketplace is beginning to recognize these negative externalities (**Figure 1**) as common to conventional agricltural landscapes. Converting annual row cropped lands to growing native deep rooted perennial plants such as wild rye eliminates these externalized ghg emissions and soil organic carbon deterioration. This loss is stopped, and soil organic carbon accruals increase, and GHG emissions are signficantly reduced [21]. As an example, in the palouse farmed lands of eastern Washington state, soil carbon stocks

Table 3: All-in costs for conventional and Wild Rye grain were estimated using USDA Green County, WI average custom farming rates and county crop yields, [15] .

Cost Differences per LB of Protein/acre

Species	% Protein	Yield (lbs) /ac		Lbs Protein/acre		Total Cost ($/ac)	$/lb protein/ac	
		Low	High	Low	High		High	Low
ELYVIR	0.21	500	1000	105	210	80	0.76	0.38
ELYCAN	0.23	200	500	46	115	120	2.61	1.04
WHEAT	0.11	600	2200	66	242	580	8.79	2.40
KERNSA	0.17	30	500	5.1	85	370	72.55	4.35

BASELINE CONVENTIONAL CROPFIELD		SOIL CARBON		
		mould board plow	ervation tillage-	Average loss national loss
CORN TO WILD RYE		Tonnes co2e/acre-yr	es co2e/acre-yr	
	Switch to no till	2	1.76	3.62
	Eliminate nitrogen fertilizers			0.59
	Annual crop production to perennials			2.77
	TOTAL EMISSIONS PER ACRE-YEAR			6.98
WILD RYE				



YEAR
0
1
2
3
4
5
6
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8
9
10

Figure 1. Soil organic carbon projections in paired, low disturbance cropped and conventionally cropped wheat/pulse fields based on repeat sampling compared with baseline sample data [16], in the Palouse agroecosystem of Washington State.

associated with no-tillage increased 2.0 tonnes Co2e/ac per year and the losses in the adjacent conventional cropped land averaged 1.76 to 2.0 tonnes Co2e/acre-yr **(Figure 1).** These measurements suggested conversion of conventional to native perennial crops has the potential to create a net positive change of up to 6.98 Tco2e/acre-year to 4.98 Tco2e/acre-year if tillage was eliminated through the process of perennilization [16]. The projected gains and losses (**Figure 1)** provide an oversimplfied graphic portrayal of the divergent nature of the soil carbon stocks under conventional and a perennial wild rye grain crop.

We further compared through a high level qualitative “Life Cycle Assessment” the conventional grain and native perennial wild rye grains (**Figure 2).** The summary suggests fundamental differences between these grain production strategies with nearly all life cycle costs for conventional annual grain having negative impacts while perennial Wild Rye appears to have primarily positive benefits.

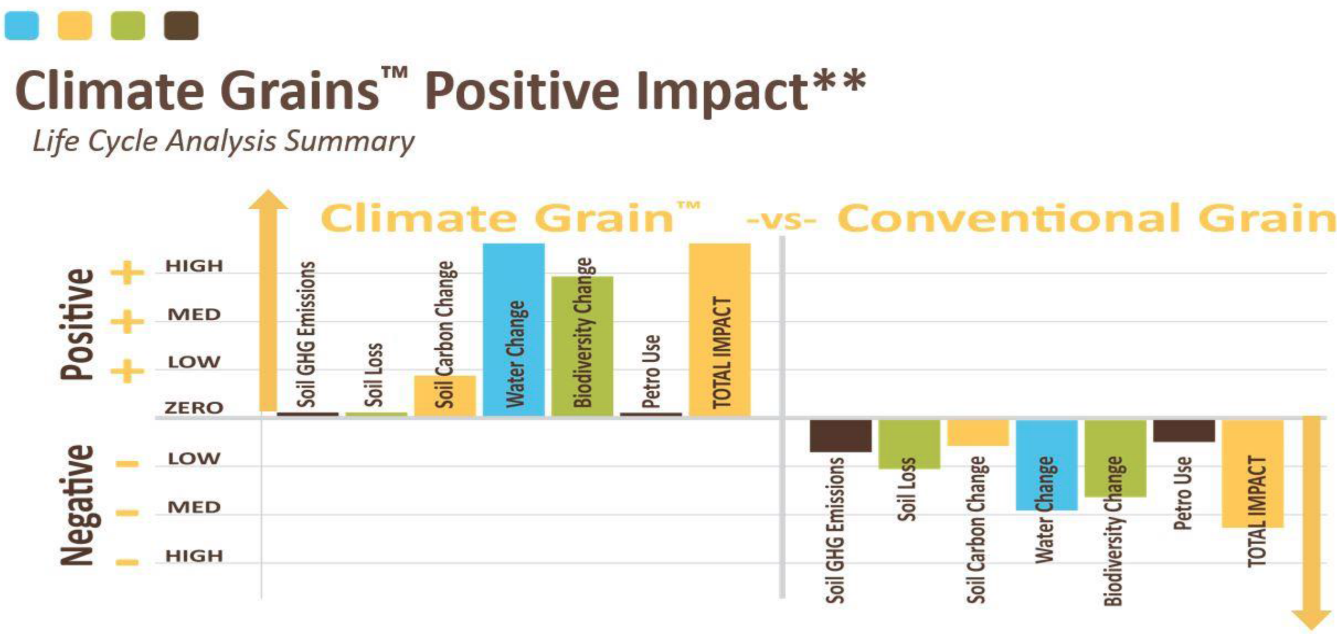
4. **If native plants become a potential new food source is protecting/restoring their habitats a conservation tool of increased importance for the future?**

We surmise that if native species become important as a human food source, protection of their habitats and wild populations is likely to be important to society and market-makers. This may suggest that costs for this protection should not be externalized, and perhaps consumer buy-in and program authenticity will depend on a proactive allocation of a portion of the funds generated from the production and sale revenues of native perennial plant foodstuffs towards protection and restoration of habitats that foster these wild native plants.

Our civilization has experienced the need to re-introduce into cultivated crops the genetics of wild progenator plants (and livestock) to reinstill disease resistance and other traits that have been lost in our crop plants through years of hybridization. As a result, conservation, protection and restoration of wild plant genetic source (habitats) locations is desirable to maintain the wild genetics. Our future food systems need to include the conservation and protection of habitats for these species from the very start in plans, budgets and financial endowments.

6. Discussion

We have explored the value of protecting and using native plant species in a future perennialized agriculture, without compromising the genetic diversity of the wild plant species, populations, or their source habitats. It appears that the principles of conservation biology and conservation genetics provide sound foundations to not compromise the genetics of these species. The principles suggest a focus on the maintenance of three areas of importance: biological diversity,



** Soil Greenhouse Gas emissions (TCo2e/ac-yr), soil loss (T/acre-yr), Soil Carbon changes (Tco2e/acre-yr), Water yield change (Runoff Total Gallons/1000 per acre-yr), Biodiversity change (% change in genomics microbial H’ diversity index averaged with Breeding bird species richness (Number of species), petroleum use/1000 in gallons/yr) and Total impact (sum of TCo2e for soil + gallons of petroleum used. All computations used emissions, soil loss, and petroleum use changes from USDA, NRCS technical manuals for annual grain crop land converted to perennial grain crops.

Figure 2: Qualitative “Life Cycle Assessment” of conventional grain verses native perennial Wild rye grains.

ecological integrity, and ecological health. Wilderness preservation and more recent genetics conservation have also focused on these key areas [13,14].

Two basic approaches to genetic resources conservation, namely, *in-situ* and *ex-situ* conservation have been deployed [13,14]. In-situ means the setting aside of natural reserves, where the species are allowed to remain in their ecosystems within a natural or properly managed ecological continuum. In-situ genetic conservation starts with not destroying or changing habitats that can endanger the animals, plants, and other organisms that live there. By effective managing these ecosystems, we can help preserve all species including threatened and endangered species and their habitat as dynamic entities capable of coping with environmental change. Ex-situ strategies take the form of gene banks (ex situ conservation) to store seeds, semen and other reproductive material, has been the primary strategy used to "maintain breeds and varieties". This approach has focused on preservation of the narrowed genetics associated with a breed.

Genetic resources for food and agriculture are the raw materials upon which the world relies to improve the productivity and quality of domesticated plant and animal populations, as well as to maintain healthy populations of wild species, including those used in forestry and fisheries. A new conservation genetic strategy is needed to work with native perennial non-woody plant species and their domestication.

Recent analyses suggest that domestication involved multiple origins of a crop from wild populations over the course of years, and perhaps from multiple geographic regions within a domestication center [22]. Agricultural societies are based primarily on domesticated annual plants that are usually self-fertile and propagated from seeds [23]. Most understandings of the effects of genetic drift and artificial selection is based on these annual plant species [24]. A domestication bottleneck (i.e., a reduction in genetic variation in cultivated populations relative to their wild relatives) often is a risk of annual plant domestication [25]. The genetic basis of domesticated traits shows that traits often are the result of single or few loci of large effect, while other domestication traits result from myriad, interacting loci of small effect [26].

On earth, perennial plants comprise ~ 80 percent of the total number of plant species, [27, 28]. Perennial plant domestications have focused on those few species we grow for their roots or tubers, or species grown for their fruits. Perennial grains have been absent from agriculture [29]. Grass family annual plants have been predictable under domestication, and the traits selected for include loss of shattering, synchronous flowering, larger grains, and more grains per inflorescence [23]. It is not known if the domestication of wild native perennial grasses will result in similar selected traits. Historically, wild plant domestication, perennial grasses and legumes have largely been overlooked because of the higher seed productivity and greater ease of growing annual plants [29].

Perennial plants differ from annual plants by longer juvenile and reproductive cycles; requiring more than a year for the seed-to-seed cycle [30,31], meaning evolution could take much longer for perennials to show divergence from their wild progenitors. The cycle time coupled with obligate outcrossing and self-incompatibility [31] can lead to increased heterozygosity within individuals, increased variation within populations, and decreased differentiation among populations as individuals exchange genes with plants from nearby populations or wild relatives [32] which can produce a nearly limitless amount of variation on which natural and artificial selection can act. Perennial plants can tolerate stochastic events over their extended lifespan, aided by higher genetic diversity, and multiple modes of propagation (seed, ramets and clonal growth [33].

Understanding the genetic basis of evolution under domestication informs the trends likely for the domestication of wild perennial species, resulting from perennial life history traits and breeding systems discussed above. Studies of tree species may suggest perennial species are resistant to founder effects during the colonization of new habitats partially due to the long juvenile phase, during which time the population can only grow via the arrival of new migrants [34], and partially due to the rapid restoration of genetic diversity via long-distance pollen dispersal (35). Similarly elevated levels of gene flow appear common in long-lived species as the oaks and poplars [36,37]. Effects of habitat fragmentation, inbreeding, or increased genetic structure among younger cohorts [38] may be as important for domestication of native wild herbaceous plants where populations locally adapted along biotic and abiotic gradients within a species range, can be quite extensive [39].

Perennial crops originated and evolved in fundamentally diverse ways than annual crops, and these differences have important implications for crop breeding and improvement [30,25,31]. In addition, domesticated perennials appear to undergo crop to wild and wild to crop gene flow. Crop-wild gene flow occurs in annual and clonal crops [42]. In perennial crops, the best-documented cases are from older domesticates (grape, olive, and apple), where gene flow occurs both from the crop into the wild species and visa versa. Gene flow from domesticated lineages back to wild populations is a conservation concern documented for apple and grape [41,42].

Evolutionary biologists and plant breeders have pursued a variety of approaches to elucidate the genetic underpinnings of domestication traits in perennial crops. Geneticists have used QTL mapping, [42] techniques for pinpointing the genetic basis of agronomically valuable traits. Genome-wide association studies [43] have been useful for differentiation between wild and domesticated lineages.

7. Nutrition, costs, and benefits of native perennial crops over annual crops

Externalized costs with conventional grain production —direct and indirect—are expensive. Dredging costs to address damages to USA waterways associated with farmland erosion and sedimentation into our nations waterways and deteriorated water quality result in hundreds of millions of dollars for maintenance and billions of dollars from deferred management of sediments. Additional deferred costs from the impacts to the nation's waterways from eutrophication, toxicology impacts to drinking water supplies (without even the costs to public health included) increase the externalized costs [44]. Impacts from GHG emissions and climate change constitute an additional exceptionally large and until now externalized cost category impacting a large part of the 3-trillion-dollar annual estimated value of the ecosystem services provided by the earth's ecosystems [4,5,6]. Deferred costs and full costs as externalities continue to accrue annually as poor management of soil, nutrient, fertilizer, herbicide, pesticide and other farm amendments and soil management techniques continue to reduce the health and viability of our nations soil productivity, future crop yields, and nutritional composition and nutrient density [7,8].

We live in an age of increasing awareness unaccompanied by sufficient appropriate responses. Whether political or personal, the responsibility to address complex problems with constructive outcomes has become challenging. Perennializing agriculture to reduce soil disruption, rebuild soil health, and contain and enrich soil nutrient content and life is potentially one of the most rapidly scalable, cost effective and both politically evocative and aligning strategies available. Increasingly farmers and ranchers, fruit and other crop producers are in search of solutions to the challenges they are experiencing on their own land: declining crop yields and quality, reduced water supplies and other impacts contributing to ever-increasing costs that are creating compelling reasons for change.

From this high-level review and examination, it appears that for every dollar invested in implementing perennialized agricultural using native deep rooted perennial wild plants, such as the wild rye, that a significant and positive multiplier effect is likely to result. Farmers could be financially incentivized to achieve the multiple benefits of perennial cropping while simultaneously also benefiting the public trust natural resources: rivers and potable water supplies and quality, biodiversity, human health, and that of other organisms; declining grassland birds, pollinators, and other life on earth. Consumers appear poised to understand this type of reinvestment in the earth, as necessary.

A framework for combining conservation biology and conservation genetics principles would appear to align nicely with and be supportive of a native perennialized agricultural future. A comparison of the costs for native perennial wild rye grain production appears to be lower than conventional annual crop grain production. It also appears that for every acre converted and dollar invested in this conversion to perennialized native grain production that significant reductions in externalized costs to society (and to deteriorating farm soil health) can be co-benefits at no additional cost. The potential improvement in human nutrition also suggests important outcomes of perennialized native plant cropping for human food.

Domestication of native plant species clearly should avoid the pitfalls of our existing agricultural enterprise system which simplified genetics and created uniformity in phenotypic expressions. Following nature's lead into a new regenerative agriculture will require fundamentally different ways of operating. It appears that native perennial crop plants can help to diversify food supplies and help address negative economic externalities in the existing human food supply chains. The unaccounted negative externalities associated with conventional agricultural grain production appear to be substantial in comparison and as only one example, to what may be achieved with perennial grain production.

8. Conclusion

The primary intent of this article was to explore the role for perennial plants in the regenerative agricultural movement. However, success of that movement ultimately depends on the public understanding the negative externalities of conventional agriculture and the positive externalities of regenerative agriculture.

The benefits of a conventional chemical driven approach to agriculture accrue as profits to the chemical companies that produce and sell the fertilizer, herbicides, fungicides, herbicides, and chemical resistant annual seeds to the farmers. The farmers benefit from higher yields and perhaps guaranteed profits through federal loans, subsidies, and crop insurance incenting them to farm in this manner. The farmers are experiencing increasing costs though in the form of declining soil health requiring increasing use of chemicals to maintain yields, resulting in declining profits per acre. The environment and humanity suffer costs in terms of the many negative externalities.

Consumers benefit in the short term from low cost food. However, long term deferred costs to human health and to remediate the negative environmental impacts appear to outweigh all benefits, including profits to the chemical industry, their captive farmers, and consumers. Moreover, many negative environmental impacts and costs to human and ecosystem health are irreversible. Overcoming the obstacles and resistance to the conversion from chemical to regenerative agriculture on a global basis is rapidly becoming a necessity for maintaining long term environmental and human health. Increasing numbers of farmers are realizing that regenerative farming is a better method, but most lack the knowledge, technical assistance, and financing to make the several year conversion to regenerative farming

Fortunately there are many for-profit and non-profit global initatives beginning to provide the leadership, capital, and expertise required to accomplish the conversion to regenerative farming. Politicians and business leaders are typically beholden to the status quo, loyal to their donors and their shareholders. Leadership and leaders to better educate the public on the full true short and long term costs and benefits of two radically different approaches to feeding humanity, and appeciation and accounting for both the positive externalities of regenerative agriculture and the negative externalities of conventional chemical reliant agriculture, are starting to rise from the farming community itself. Because farmers and ranchers most reliably change and through peer to peer learning, this full story must be told, as the agents of change by them. Through their communciations and trust building, with support, they are begining to inspire and encourage others to make the conversion and realize the direct benefits and positive externalities inherent in regenerative agriculture. An understanding of the negative eternalities that plague conventional agriculture will engender consumer fear, disgust, and support for change to a better way. An understanding of the direct benefits and postive externalies of regenerative agriculture will motive consumers to pay at least a modest premium for regeneratively grown food. An informed and motivated public combined with the ultimate higher profitability of regenerative agriculture will win the day. This is an all encompassing win win win for the environment, farmers, and humanity!

9. Author Contributions

Apfelbaum contributed to manuscript drafting, framing the issues, and Elstrott edited, reviewed, and contributed to economic discussions.

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11. Data Availability Statement

Not applicable.

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13. Conflicts of Interest

The authors declare no conflict of interest.

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