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David Pimentel consistently promoted perennial grains as the future of agriculture

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Abstract

David Pimentel was trained as an entomologist, but he was widely recognized for investigating and revealing uncomfortable knowledge on the state of global agriculture, covering topics of energy, soil erosion, biodiversity loss, pesticide contamination and energy use. While outspoken in his bold assessments of agriculture's environmental and energetic shortcomings, he was less forthcoming with proposals for equally bold solutions. Yet one highly transformative idea that he raised repeatedly in his career after co-authoring a seminal paper in 1986 with researchers at The Land Institute was the breeding of perennial grain crops to replace annual grains on the landscape. In this paper, we look holistically at the work of David Pimentel to interpret his views on the prospects for plant breeders to develop perennial grains and the challenges that perennial grains could help address. As society continues to grapple with profound agricultural challenges, it is relevant that one of the last century's most prominent and comprehensive scholars of agriculture honed in on perennial grains as the bold solution that would simultaneously address multiple complex environmental challenges while reducing human labor and fossil fuel dependency.

Keywords Perennial grains · Erosion · Fossil fuel · Water · Sustainable agriculture · Biotechnology

> Clearly, much can be learned from natural systems about maintaining the productivity and sustainability of agricultural systems. If the agricultural production system could be designed to more closely resemble natural ecological systems, it would require fewer energy inputs and be more productive and sustainable.
>
> Pimentel and Pimentel (2008) p. 32

David Pimentel, Professor of Insect Ecology and Agricultural Sciences in the Department of Entomology at Cornell University, returned to the earth in December 2019 at age 94. He was widely known as a scientist unfazed by crossing disciplines to assess and expose major disparities between the human economy and nature's economy, especially with respect to the human contrived ecosystems of agriculture. Few if any scientists of his generation

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published as many articles, chapters or books on such disparate topics as soil erosion, energy, biological control of pests, over population, environmental and economic costs of pesticides, biodiversity loss, diminishing water resources, food consumption patterns, invasive species, human disease and even nuclear war, frequently in very high impact journals. But David Pimentel did not focus on any topic in isolation. As a fervent ecologist, he would go to great lengths to identify and explore relationships between topics. For example, in a widely cited paper on water resources (Pimentel et al., 1997a), Pimentel and his co-authors tied challenges with water resources to biodiversity loss, climate change, disease transmission, energy use, diet and societal conflicts.

From the mid-1980s to his retirement, Pimentel was known among the life science faculty and students at Cornell University to offer experiential training to undergraduates and graduate students in writing review papers that addressed critical environmental issues including policy implications. In addition to helping students develop valuable skills, this opportunity served to empower cadres of motivated students from diverse disciplines and backgrounds to explore a wide scope of literature that effectively underpinned interdisciplinary papers on topics that included soil erosion (Pimentel, 1987), biodiversity (Pimentel et al., 1992a), environmental and economic costs of pesticide use (Pimentel et al., 1992b), renewable energy (Pimentel et al., 1994a, 2002), water resources (Pimentel et al., 1997a), and the limits to human population growth (Pimentel et al., 2010). The final review paper that Pimentel orchestrated with Cornell students was an ecological, economic and energetic comparison of annual and perennial grains (Pimentel et al., 2012).

1 Uncomfortable knowledge

David Pimentel will be remembered for his relentless drive to reveal uncomfortable knowledge with respect to fundamental ecological underpinnings and shortcomings of food production. While he wrote primarily for scientific audiences in peer-reviewed journals, one of the Pimentel's hallmarks was to craft high impact, easily understandable statements and/or calculations that would attract attention from the media and policy makers. He was especially committed to (and fearless in) calculating the value of externalities that were either "ecosystem services" or forms of environmental degradation that were unaccounted for by the market. Pimentel clearly believed that representing the true cost of externalities would serve as a wakeup call to policy makers and the public at large. His role as an agricultural whistle blower was especially powerful given his affiliation with one of the most prominent land grant universities in the USA. Historically, narratives describing the state of agriculture that are promoted by land grant universities have leaned heavily toward technological optimism and other simplified accounts that obscure complex social and ecological challenges (Rayner, 2012). Examples of Pimentel's high impact statements include:

- The approximately 50,000 nonindigenous species in the USA cause major environmental damage and losses totaling approximately $137 billion per year (Pimentel et al., 2000).
- The estimated total of $839 million annual losses attributed to environmental and social costs of pesticide use represents only a small portion of the actual cost (Pimentel et al., 1980).
- The annual economic and environmental benefits of biodiversity in the USA total approximately $300 billion (Pimentel et al., 1997b).

- If off-site and on-site costs are combined, the total cost of erosion from agriculture in the USA is about $44 billion per year, or about $100 per hectare of cropland and pasture. This erosion cost increases production costs by about 255% each year (Pimentel et al., 1995).
- An assessment was made of the role of forests and non-timber products in the food system of developing countries. A total of about $90 billion in non-timber products are harvested each year (Pimentel et al., 1997c).
- Less than 0.1% of pesticides applied for pest control reach their target pests. Thus, more than 99.9% of pesticides used move into the environment where they adversely affect public health and beneficial biota, and contaminate soil, water and the atmosphere of the ecosystem (Pimentel, 1995).
- In developed countries the use of natural resources may be 100–600-fold more per capita than in developing countries. This excessive consumption diminishes biodiversity directly (Pimentel et al., 1992a).
- The evidence suggests that more biological diversity exists in the agricultural/forestry and other human managed ecosystems because human managed ecosystems cover approximately 95% of the terrestrial environment (Pimentel et al., 1992a).
- Despite all efforts to control pests, approximately 35% of all crop production is lost to pests (Pimentel, 1991).
- Does human society want 10–15 billion humans living in poverty and malnourishment or 1–2 billion living with abundant resources and a quality environment (Pimentel et al., 1994b)?

Less common in Pimentel's writings were detailed descriptions of possible solutions to the challenges he brought to light. For example, Pimentel would list solutions to soil erosion such as mulches, no till, ridge till, grass strips, shelterbelts, terracing, contour planting and crop rotations, but offer little quantitative evidence of their relative efficacy (Pimentel & Kounang, 1998). An important exception would be his extensive work on regulating crop pests with crop diversity and other biological control strategies. Another exception, and one we will focus on for the remainder of this paper, was his understated but persistent interest in perennial grains that spanned two-thirds of his career. In an effort to understand David Pimentel's views on perennial grains, we assembled a chronology of his writings in which they were discussed. Given his extensive publication record, we cannot be certain that our account is comprehensive, but we are confident that it is nearly so. In undertaking this exercise, we were interested to learn: (1) what problems in agriculture did Pimentel think would be addressed with perennial grains? (2) did his interest occur at a particular stage of his career or did it persist over time? (3) did Pimentel think the development of perennial grains was feasible and if so, how would they be bred? (4) were his views on perennial grains in close alignment with those of researchers at The Land Institute who were dedicated to developing perennial grains? and (5) what might Pimentel's longstanding interest in and support for perennial grain development convey to the agricultural research community today as we continue to struggle with virtually all of the same issues Pimentel wrote about throughout his career?

2 David Pimentel's perennial interest in perennial grains

In 1986, David Pimentel was the first author on a paper published in *Interdisciplinary Science Reviews* titled Perennial Grains: An ecology of new crops. His three co-authors, Wes Jackson, Marty Bender and Walter Pickett, were all associated with The Land Institute in Salina, Kansas, in the roles of co-founder, research associate and chief plant breeder, respectively. Today, The Land Institute has been in existence for almost a half century and is recognized as a leading organization in the global movement to develop agricultural ecosystems that capture critical functions of natural ecosystems primarily through the integration of perennial species and greater crop diversity (Crews et al., 2018). The work that was reported in that manuscript took place in late 1983–early 1984. At the time The Land Institute was eight years old and had only just begun to narrow its focus on the potential for herbaceous perennial polycultures to address what Jackson referred to as the 10,000-year-old problem *of* agriculture (Jackson, 1980). This 1986 paper was one of the very first, if not the first, peer-reviewed publication on the early work of The Land Institute to identify perennial grain candidates (Wes Jackson, Pers comm.).

The year after the *Interdisciplinary Science Review* paper, Pimentel authored a review of the book *Partners Against Hunger* by World Bank economist Warren Baum (Pimentel, 1987). The book explores Baum's perspectives on the Consultative Group on International Agriculture Research (CGIAR), and the Green Revolution it helped to orchestrate. Pimentel's review offers little critique of what Baum wrote in his book, but instead focused on what he left out, namely meaningful discussion of the environmental and resource impacts associated with the Green Revolution. According to Pimentel, soil erosion, eutrophication from nutrient runoff, increased pesticide use and loss of genetic diversity are all topics that should have been covered in Baum's work. At the end of his review, Pimentel wrote:

> In his discussion of the anticipated contributions of biotechnology, Baum also does not mention the need for perennial grains. Current technologies could provide weed control for the five-to-six-year life spans of perennial grains once the crops are developed. The use of perennial grains would reduce human labor and fossil-fuel energy inputs to crop production while decreasing soil erosion and associated problems. The development of perennial grains for both temperate and tropical regions should receive high priority in biotechnology programs.

Two things are surprising about this statement made in 1987. The first is how matter-of-factly Pimentel raised the topic of perennial grains, as if they were a widely recognized possibility that Baum should have been aware of. The second surprising aspect of this comment was how Pimentel clearly saw the use of biotechnology as the key to developing perennial grains. We return to this point below.

In 1989, The Land Institute sponsored a meeting in Salina, Kansas, called "The Marriage of Ecology and Agriculture" that brought together a group of highly regarded ecologists, agricultural scientists, authors and policy makers to discuss how agriculture might be reinvented to capture key attributes of natural ecosystems. Included in this meeting were Jack Ewel, Alison Power, Herb Bormann, Wendell Berry, Major Goodman and David Pimentel.

Three years after the workshop, Pimentel penned a favorable review for the book *Farming in Nature's Image*, written by Land Institute research staff Jon Piper and Judith Soule (Soule & Piper, 1992). Published in *BioScience*, the review summarized and added to the book's critique of industrial agriculture, and finished with an enthusiastic pitch for the promise of perennial agriculture (Pimentel, 1992):

> The eventual development of perennial crops will be a tremendous boon to world agriculture. Assuming that the perennial crops would remain effective for five to six years, the advantages would be: reduced plowing and a reduction in the enormous amount of energy used in tilling the soil annually, reduced soil erosion and rapid

> water runoff because the land will be continuously covered with crop vegetation, reduced number of seeds to be planted each year, fewer crops lost to either cold-wet or dry spring planting weather, and better pest control with fewer pesticides required.

In the fourteen years following the review of *Farming in Nature's Image*, Pimentel's writing on perennial grains primarily focused on how genetic engineering could and should be used to develop perennial versions of the major grain crops (Paoletti & Pimentel, 1996; Pimentel, 2000, 2004). In addition to this biotechnology theme, another perennial grain topic appeared in a paper produced by one of Pimentel's graduate student courses on the Economic and Environmental Benefits of Biodiversity (Pimentel et al., 1997b). In this work, the authors took the bold step of estimating the economic benefits associated with ecosystem services that would be provided by perennial grains should they be developed. Pimentel et al. calculated that reduced soil erosion, tractor fuel inputs, and reduced pollution associated with agrochemicals would result in $20 billion per year in economic benefits for US citizens and $170 billion per year worldwide. To our knowledge, no other attempts have been made to quantify the potential global economic impacts of perennial grains.

In 2006, David Pimentel and his wife Marcia published a paper on "Global environmental resources versus world population growth" in *Ecological Economics* (Pimentel & Pimentel, 2006). The paper began with questions,

> What will be required of us to secure a quality life for future generations of the world? Will there be sufficient land, water, energy and biological resources to provide adequate food and other essential human needs? Threatening to overwhelm the availability of these basic world resources are the fundamental needs for food and other human resources required by the expanding human population.

and ended with three specific future outlooks,

> Serious efforts must be made to improve our basic food crops such as developing perennial grains and pest resistant crops, and improving the nutritional makeup of major crops. Concurrently, the transition to reliable renewable energy resources must be a focus.

Two years following the paper on resources and population growth in *Ecological Economics*, David again joined authorship with Marcia in 2008 publishing the third edition of *Food, Energy and Society*. Included in the chapter on Ecological Systems, Natural Resources, and Food Supplies, a specific section was dedicated to "Annual versus Perennial Crops," foreshadowing the 2012 paper by the same title mentioned above. Although not extensive, the language in this volume was the strongest to date highlighting the potential advantages of perennial grain crops relative to annual species. In particular, perennials were seen as a potentially significant solution to unsustainable rates of soil erosion and fossil fuel use in conventional grain agriculture. As documented previously, Pimentel and Pimentel posit that the development of perennial grains "will depend in part on genetic engineering, which in turn depends on maintaining biological diversity (p. 31)."

In 2011, David Pimentel co-authored a paper that juxtaposed established and emerging approaches to sustainable agriculture, including agroecology, agricultural intensification, integrated agriculture, organic agriculture, permaculture, precision agriculture, perennial crops and transgenic technology (Gomiero et al., 2011). In their treatment of perennial crops, they emphasized improvements in ecological functions such as nutrient retention, efficient water uptake and carbon sequestration that perennial grains were predicted to achieve relative to annuals. The authors also tied these improvements in ecosystem functions to anticipated reductions in agrochemical and fossil fuel inputs. In describing perennial crops under development, it was interesting that unlike in previous articles, no mention was made of efforts to perennialize annual grain crops such as wheat, sorghum and rice through wide hybridization between existing annual species and perennial relatives.

Twenty-six years after David Pimentel was the first author on a paper focused exclusively on the development of perennial grains to address shortcomings of annual agriculture (Pimentel et al., 1986), he appeared as the first author on a second paper with a similar focus (Pimentel et al., 2012). Co-authors of the 1986 paper were the original perennial grain researchers at The Land Institute, a fledgling non-profit organization that became dedicated to introducing key functional features of natural ecosystems such as perenniality and diversity into agricultural ecosystems. Co-authors of the 2012 paper were graduate students at Cornell University. In this article, we have listed most if not all of the papers that were published between 1986 and 2012 in which Pimentel identifies the development of perennial grains as a promising approach to improving on numerous dimensions of agricultural sustainability. In these works, Pimentel and co-authors consistently highlight how perennial grains have the potential to curtail soil erosion, reduce fossil fuel dependency, improve on water infiltration and uptake efficiency—all topics that were central to his life's work. While he offered enthusiastic endorsements for the promise of perennial grains, only in his 1986 and 2012 papers does he, along with co-authors, dive into any details of the ecology, crop development and social ramifications of perennial grains. We will contrast these papers to address the first two questions we raised earlier: (1) what problems in agriculture did Pimentel see being addressed with perennial grains? and (2) did his interest occur at a particular stage of his career or did it persist over time?

3 The most relevant benefits of perennial grains

Pimentel's 1986 and 2012 perennial grains papers illustrate how much of his justification for developing perennial grains remained constant over decades (Table 1). The list of ecosystem functions that would improve in a shift to perennial grains expanded by 2012 to include soil carbon sequestration, soil health and wildlife habitat—all social concerns that had risen in prominence in recent decades. The 2012 paper also included discussion of social advantages such as food security and farmer profitability. The list of perennial crop candidates narrowed considerably as Pimentel and colleagues chose to focus primarily on the perennialization of the major grain crops rice, wheat and maize (2012). The more extensive list of species described in 1986 reflected the early, exploratory phase of evaluating perennial crop candidates by Land Institute researchers (Table 1).

4 The feasibility of breeding perennial grains

The third question we raised earlier was whether Pimentel thought the development of perennial grains was feasible and if so, how would they be bred? As we have alluded to already, Pimentel's writings conveyed an unambiguous answer to this question: yes. Breeding perennial grains was *now* feasible due to the advent of genetic engineering. While Pimentel includes the use of molecular tools such as marker-assisted selection in how he defined genetic engineering, it is clear from the examples he and his co-authors discuss that

Table 1 Features of perennial grain agriculture considered by Pimentel and colleagues in 1986 and 2012

	1986[a]	2012[b]
Improved ecosystem functions relative to annual grains		
Reduced soil erosion from reduced tillage	+	+
Reduced water runoff	+	+
Increased nutrient retention	+	+
Reduced energy for tillage and nutrient amendments	+	+
Improved soil health		+
Increased soil carbon sequestration		+
Improved wildlife habitat		+
Potential pest challenges in perennial cropping systems		
Weed competition, especially during establishment	+	+
Insect herbivory	+	+
Pathogen pressures	+	+
Social benefits of perennial grains		
Greater food security		+
Potentially economically viable		+
Other topics		
Consideration of diversity alongside perenniality	+	
Physiological tradeoff of yield and perenniality	+	+
Perennial crops under development—domestication projects		
Alta fescue (*Festuca arundinacea*)	+	
Buffalo grass (*Buchloe dactyloides*)	+	
Cider milkvetch (*Astragalus cicer*)	+	
Curly dock (*Rumex spp.*)	+	
Eastern gamma grass (*Tripsacum dactyloides*)	+	
Giant wild rye (*Elymus giganteus*)	+	
Illinois bundleflower (*Desmanthus illinoensis*)	+	
Intermediate wheatgrass (Kernza®) (*Thinopyrum intermedium*)	+	+
Lesquerella (oilseed)		+
Lepidium (oilseed)		+
Sainfoin (Baki bean®) (*Onobrychis viciaefolia*)	+	
Sand dropseed (*Sporobolus cryptandrus*)	+	
Sunflower (*Helianthus maximiliani*)	+	+
Wild senna (*Cassia marilandica*)	+	
Perennial crops under development—wide hybridization projects		
Maize (*Z. mays x Tripsacum dactyloides, Zea diploperennis* or Z. *perennis*)	+	+
Rice (*Oryza sativa* x *O. longistaminata*)		+
Rye (*Secale cereale* x *S. montanum*)	+	
Sorghum (*Sorghum bicolor* x *S. halapense*)	+	+
Sunflower (*Helianthus annus* x perennial *Helianthus* and other genera)	+	+
Wheat (*Triticum* spp. x *Thinopyrum* (*Agropyron*) spp.	+	+

[a]Derived from Pimentel et al. (1986)

[b]Derived from Pimentel et al. (2012)

he is primarily referring to transgenic manipulations (Paoletti & Pimentel, 1996). To the extent that non-invasive molecular tools constitute genetic engineering, his prediction was correct. A wide range of such tools have been used to accelerate breeding progress including marker-assisted selection, genomic selection and genome-wide association studies (GWAS) (Crain et al., 2020; Crews & Cattani, 2018; Zhang et al., 2022). With respect to using molecular tools to directly manipulate plant genes, researchers have begun to experiment with targeted mutagenesis using gene editing in laboratory populations to identify or verify the genetic basis of specific domestication traits (Chapman et al., 2022) such as non-shattering. Pimentel makes several references to converting annual grains such as corn or wheat into perennials using genetic engineering (e.g., Pimentel, 2000). Presumably he is referring to transgenic technologies. Contrary to Pimentel's expectation, no transgenic manipulations that we are aware of have been used to breed the wide hybrid crosses under development today. Current hybrid crosses involving wheat, rice and sorghum have been achieved with traditional cross pollination. Moreover, similar non-transgenic approaches have been used to advance de novo domestication of new perennial crops, something Pimentel did not acknowledge after the first co-authored paper in 1986 (Crews & Cattani, 2018).

It is noteworthy that in the 1986 paper co-authored by Pimentel and Land Institute researchers, no mention was made of using wide hybridization between annual rice and a perennial relative to breed a perennial rice. In contrast, the 2012 manuscript by Pimentel and grad students essentially predicted that rice would be the first high-yielding perennial grain to be developed. Indeed, this prediction has arguably come true. A recent paper reported on perennial rice (PR23) cultivars developed in the Yunnan Province of China that yield similarly to annual varieties with an average of 6.8 Mg ha^{-1} $harvest^{-1}$ (Zhang et al., 2022). PR23 is currently being grown by over 44,000 smallholder farmers in SW China, with a single planting producing grain for eight consecutive seasons (Zhang et al., 2022). Contrary to Pimentel's prediction, however, no genetic engineering was used in achieving the wide hybrid cross between annual rice (*Oryza sativa*) and its perennial relative (*Oryza longistaminata*).

5 Is perenniality enough? Or is diversity lacking too?

The fourth question we raised above was whether Pimentel's views on perennial grains were in close alignment with those of researchers at The Land Institute who have been dedicated to developing perennial grains. The Land Institute's co-founder, Wes Jackson, frequently emphasized problems *of* agriculture in contrast to problems *in* agriculture to differentiate challenges that were inherent in the design of the agricultural ecosystem, as opposed to those that simply required adjustments in the existing system to be solved (Jackson, 1980). Jackson argued that the most challenging problems of agriculture could only be addressed if our food producing ecosystem was to be reimagined and remade so that it more closely resembled the structure and thus captured the function of natural terrestrial ecosystems (Jackson & Piper, 1989). In particular, Jackson identified diversity and perenniality as key attributes missing from grain agroecosystems. Throughout his publication record, we did not see Pimentel discuss or adopt the distinction between problems *of* and problems *in* agriculture, but based on his multi-faceted critique of annual grain agriculture that encompassed everything from the mechanisms underlying outbreaks of insect herbivores and pathogens (low diversity) and soil erosion (tillage), and energy inputs (compensating for inefficiencies like nitrogen and water loss) he clearly understood the system-level shortcomings of annual cropping systems.

Another example of where Pimentel appeared to diverge from Wes Jackson and other researchers at The Land Institute, at least in his writings, was how he addressed crop diversity and perenniality separately. In the 1986 paper Pimentel co-authored with Wes Jackson and others, diversity and perenniality were discussed as critical interacting components of natural systems and central to a truly sustainable agriculture (Table 1). That an ecosystem approach combining perenniality and diversity appeared in Pimentel's first paper on perennial grains may reflect the perspective of his co-authors more than his own. In contrast to the 1986 paper, virtually all perennial grain writings of Pimentel's over the next 33 years, including the 2012 paper, did not in any way link or frame perenniality with diversity. This could be attributed to how overarching the topic of diversity was in Pimentel's career—indeed it was the subject that launched his interest in alternative agriculture (Pimentel, 1961). Nevertheless, it remains notable that Pimentel did not follow the model of The Land Institute by linking diversity and perenniality to describe an agriculture inspired by the structure and function of natural systems.

We have described how over the decades that David Pimentel periodically wrote about perennial grains, he would always explain how effective they would be at curbing soil erosion, dependency on fossil fuels, and waste of water resources. Given Pimentel's consistently strong endorsement for a perennial solution to many of agriculture's most profound challenges, we were surprised at finding no mention of perennial grains as a potential solution or even a good idea in his countless papers on erosion, energy and water (e.g., Pimentel & Burgess, 2013; Pimentel & Kounang, 1998; Pimentel et al., 1987, 1995, 2004; Pimentel, 2009, 2011). In numerous papers he detailed mechanisms underlying soil erosion, chief among them was the removal of natural vegetation that protected soils from the impacts of rain and wind. For example, in a paper written in 2013, the year after the 2012 review on perennial grains, Pimentel and Burgess (2013) wrote an extensive paper detailing the causes of soil erosion and potential solutions. While the removal of vegetative cover was referenced repeatedly, the authors did not point out that the vegetation of the natural ecosystems under which soil development took place was overwhelmingly perennial and that the lack of perennial grain crops helps explain why agriculture predictably experiences unsustainable erosion losses. Was David Pimentel concerned that the credibility of his urgent policy messaging might be compromised by acknowledging what at the time was a fringe idea to transform agriculture? In other words, were perennial grains too uncomfortable of a solution to promote to all audiences? Why perennial grains were not mentioned as even a moonshot idea in most of his writings that addressed problems in agriculture will remain unknown. It remains possible that he thought of them as distinct, solvable problems *in* agriculture, as opposed to related problems *of* agriculture. However, given how interdisciplinary Pimentel's thinking was in most arenas, it seems difficult to believe that he was not seeing perennial grains for what they were—a large step toward reconciling the human economy with nature's economy.

6 Why Pimentel's interest in perennial grains matters today

David Pimentel published 690 papers and 40 books in his inspired career as a researcher, teacher, civil servant, and policy advocate (Kassam, 2021). Under 3% of his published work mentioned the idea of breeding perennial grains to improve on agricultural sustainability. However, perennial grains persisted in his mind's toolbox of important possibilities as he raised the topic in his writing repeatedly over most of his career after 1986. Shortly before his death in 2019, in an interview with Peggy Bradley, Pimentel made the following final endorsement of the transformative potential of perennial grain agriculture.

> "Grains make up 80% of our food today in the world, and all of these grains we are using are annual grains which means you have to till the soil and use the seeds to plant your corn and soybeans or other grains. Just think of the energy you could save if you had perennial grains, and when I say perennial [it] is to plant grains once every 5-6 years. Poor people in developing countries in particular (I suppose we could look at ourselves in the future) [would not] have to till that soil to replant and/or use [their] corn and other grains to [sow] in the soil every year…. But we don't have perennial grains right now, there's a little bit of research on it but you see industry is not interested in [it]. That's not them. It's public research that would [make the most sense]…at least 25 years of research–so that's [far] off. There is a wheat that you plant, and it comes up and you harvest the wheat in the fall and comes up in the spring. There's [progress on] sorghum, that does that same thing. A perennial crop [that is] not a grain, is alfalfa where you harvest it every year for 5 or 6 years and then you have to till the soil and replant it. Clover is somewhat similar. So, we are not talking about [establishing] it in the soil and [it goes on] forever, but if you don't have to till that soil every year,… that's a major effort—tilling the soil is one of the most costly energy inputs right now. People in developing countries, you see, are caught up in having to till the soil—I mean if they are fortunate to have a horse or oxen or a tractor, [they're] better [off], but if you have to till by hand—for example we (in developed countries) currently raise corn with an input of 5 hours per hectare per year, if you're doing it all by hand, you're talking 500 hours of time….it's true! So it's a tough situation. (Bradley, 2019)

Does David Pimentel's 33-year interest in and advocacy for perennial grain development carry any relevance to the agricultural research community today? Few researchers in the last century have worked to understand the breadth and depth of environmental and social crises in agriculture as David Pimentel. He delivered uncomfortable knowledge to graduate students, fellow researchers, policy makers and the general public. He was a man who had an extraordinarily broad perspective on the complexity of our species' tendencies, needs and desires—from population growth and dietary choices to the exhaustion of natural resources, and our rapid shift from solar to fossil energy. That Pimentel zeroed in specifically on perennial grains as a solution that could remake agriculture and address numerous challenges, is not only worthy of acknowledging, it is worthy of action. The recent advances that have been achieved in perennial grain breeding (Bajgain et al., 2023; Kong et al., 2022; Zhang et al., 2022), agroecology (Crews et al., 2022; Peixoto et al., 2022; Sprunger et al., 2020), and social adoption (Streit Krug & Tesdell, 2020; Streit Krug et al., 2023) with relatively minor investment from public and private sources (DeHaan et al., 2023) underscore the potential to make rapid progress if society more follows the lead of David Pimentel and fully commits to a perennial future.

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Declarations

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