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Sustainable commercialization of new crops for the agricultural bioeconomy

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Abstract

Diversification of agroecological systems to enhance agrobiodiversity is likely to be critical to advancing environmental, economic, and social sustainability of agriculture. Temperate-zone agroecological systems that are currently organized for production of summer-annual crops can be diversified by integration of fallow-season and perennial crops. Integration of such crops can improve sustainability of these agroecological systems, with minimal interference with current agricultural production. Importantly, these crops can provide feedstocks for a wide range of new bio-products that are forming a new agricultural bioeconomy, potentially providing greatly increased economic incentives for diversification. However, while there are many fallow-season and perennial crops that might be used in such a "bioeconomic" strategy for diversification, most are not yet well adapted and highly-marketable. Efforts are underway to enhance adaptation and marketability of many such crops. Critically, these efforts require a strategic approach that addresses the inherent complexity of these projects. We outline a suitable approach, which we term "sustainable commercialization": a coordinated innovation process that integrates a new crop into the agriculture of a region, while intentionally addressing economic, environmental and social sustainability challenges via multi-stakeholder governance. This approach centers on a concerted effort to coordinate and govern innovation in three critical areas: germplasm development, multifunctional agroecosystem design and management, and development of end uses, supply chains, and markets. To exemplify the approach, we describe an ongoing effort to commercialize a new fallow-season crop, field pennycress (*Thlaspi arvense* L.).

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Introduction

Society is now calling on agriculture to provide goods and services that begin with enhanced production of food and other materials, but range far beyond. For example, agriculture is under increasing pressure to achieve complex sustainability goals such as food security, stewardship of biodiversity, compatibility with energy and water systems, and resilience to climate change and other potential "shocks" (Loos et al., 2014; Allan et al., 2015). Diversification of agroecological systems to enhance agrobiodiversity is likely to be critical to advancing such complex sustainability goals (Bennett et al., 2014; Pretty and Bharucha, 2014). Development of a wide range of novel annual and perennial crops is increasingly seen as central to diversification (Dias, 2015), as these crops can be integrated with current agricultural production systems to boost the biological and economic diversity of these systems (Kremen and Miles, 2012). However, diversification via integration of new crops is greatly hindered by barriers, including lack of commercial viability, and the challenges of integrating new crops into agroecological systems.

Now, a wave of innovation is creating new opportunities to surmount such barriers. Germplasm development can now proceed much more rapidly and inexpensively than in past decades, propelled by recent advances in genomic sciences, which can be applied to fallow-season and perennial crops that have received relatively little genetic improvement (Hartung and Schiemann, 2014). New spatial-information technologies are advancing understanding of how diversification can efficiently improve the environmental sustainability of agroecological systems (e.g., Dosskey et al., 2015). Finally, end-use, supply chain and market development for these crops has greatly advanced as a result of public and private sector efforts to develop a wide range of new bio-based products, including new foods, feeds, bioproducts, biomaterials, and biofuels (Chen and Zhang, 2015). These recent and ongoing advances enable these three areas of innovation—germplasm development, agroecosystem diversification, and end-use/markets—to be coordinated and integrated on the same time scale, whereas previously, germplasm development was a much slower process (Runck et al., 2014).

The latter area of innovation—involving new bio-based products—is driving rapid development of a new agricultural "bioeconomy", which is expected to become an significant part of the global economy (Jordan et al., 2007; McCormick & Kautto, 2013). These economic and technological dynamics are creating major opportunities for diversification and increased sustainability via cultivation of new crops that produce bio-economy feedstocks (e.g, biomass and oils). These opportunities are particularly attractive because feedstock commodities for bio-products can be produced by integrating fallow-season and perennial crops in summer-annual crop production systems, thus achieving their diversification (Chen and Zhang, 2015). This integration can be accomplished without major interference with current food production, and with potentially large improvements in environmental, economic and social aspects of sustainability (Dale et al., 2014). Demand for new feedstock commodities can thus drive increased adoption of new crops, diversification of agroecosystems, and significant enhancements in sustainability of agroecological systems.

However, the range of innovation—and coordination thereof—that is needed to advance diversification by new crop development of course presents a complex challenge. Therefore, an approach to crop development and commercialization that can meet this challenge is necessary. In our view, the need for such an approach has not been widely recognized. To advance awareness of the issues involved in such development and commercialization, and to stimulate critical reflection among interested parties, we offer this commentary. We consider the challenges that commercialization must meet, outline an approach for doing so, and exemplify the approach with a current case.

We argue that a coordinated innovation process is needed that can integrate profitable production of a new crop into the agriculture of a region, while addressing economic, environmental and social sustainability challenges of such integration. We term such a process "sustainable commercialization", in accord with the sense of "commercialization" as "introducing some product into commerce". Our meaning is not confined to marketing efforts or product positioning in a market, but rather is broad and systemic, addressing all aspects of introducing a new crop into commerce, while addressing associated sustainability challenges related to economic, environmental and social aspects of commercialization. Our effort to implement sustainable commercialization centers on a concerted effort to coordinate and govern innovation in the three critical areas noted above: crop germplasm development, integration in existing agroecological systems, and development and marketing of new commodities (Runck et al., 2014).

Sustainable commercialization is an inherently challenging enterprise, because it is a complex problem (Peterson, 2009). Complex problems are multi-dimensional, poorly understood, and diversely-defined by interested parties (Schut et al., 2015). Sustainable commercialization is highly dimensional, affecting—and affected by—a wide range of biophysical, technological, socio-cultural, economic, institutional and political factors. Understanding of many of these factors and their dynamic interactions is limited. Finally, sustainable commercialization involves the interests of multiple stakeholder groups that are likely to view the issues of commercialization quite differently. For example, extensive integration of a new crop into the agriculture of a region will have many environmental, economic, and social effects, with inevitable tradeoff among effects, and regional groups concerned with these tradeoffs are likely to view them differently (Haughton et al., 2009).

Given the inherent complexity of sustainable commercialization, methods are required that can address that complexity. If not addressed, commercialization of new crops may occur, but not achieve their full potential to improve sustainability. Secondly, failure to address complexity may lead to problems that increase the cost and risk of investments in commercialization, thereby discouraging investment. Below, we illustrate our proposal by outlining a comprehensive strategy for sustainable commercialization of a new oilseed crop, field pennycress, (*Thlaspi arvense* L., Figure 1). The authors of this commentary are presently engaged in implementation of this strategy for this species.

Lessons learned in our project pertain to new fallow-season and perennial crops being developed for diversification of agriculture in central North America by the Forever Green Initiative (Runck et al., 2014). The authors are all participants in that project, which is led by the University of Minnesota and involves circa 60 researchers in fifteen disciplines (ranging from genomics to landscape architecture), and a wide range of research and commercialization partners. The Initiative is developing a portfolio of crops that produce feedstocks for a wide range of bio-products; crops include herbaceous perennials (e.g., perennial sunflowers, perennial wheat, and promising native species), fallow-season crops (e.g., pennycress, winter barley, camelina,

Figure 1

A pennycress production trial near Peoria, Illinois.

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and winter pea) and woody perennial crops (e.g., willows and hazelnuts). The Initiative is supported by funding from the MN Legislature, a wide range of state and federal agencies, and from a range of firms.

The Initiative is a concerted effort to develop promising options for diversification with species that improve productivity, efficiency, and adaptability to variable climates. However, we are keenly aware of the complexity of commercialization of these species. Our effort to develop effective and efficient methods for sustainable commercialization, as outlined in this commentary, aims to support the Forever Green Initiative, and as well, the global project of new crop development for diversification (Dias et al., 2015). We begin by outlining the opportunities for diversification via extensive cultivation of pennycress in the US Midwest, and the complex challenges that this diversification project faces.

Field pennycress – a promising vehicle for diversification

In the US Midwest, pennycress is being developed as a winter-hardy oilseed crop that can be double- and relay-cropped to diversify agroecological systems presently dominated by the summer-annual crops maize and soybean (Moser et al., 2009; Phippen and Phippen, 2012). Pennycress possesses many traits that can support its integration in existing maize-soybean agroecological systems. Specifically, it is highly cold-tolerant and provides a living crop that covers land over winter, reducing soil erosion and nutrient leaching, and providing habitat for animals and insects (Dean and Weil, 2009; Moore and Karlen, 2013; Groeneveld et al., 2014). In spring, established pennycress suppresses weed growth (Johnson et al., 2015), which could reduce herbicide usage and diversify weed management strategies. Pennycress also offers a foraging resource to insect pollinators early in spring, when few floral resources are available (Groeneveld and Klein, 2014). Pennycress can provide sizeable yields of oil-rich seeds (Hojilla-Evangelista et al., 2013). For example, pennycress and soybeans produced 18–20% more oilseed yield per acre than soybean alone, despite modest reductions in soybean yields (Johnson et al. 2015). Trials in a warmer region (Illinois) have shown no soybean yield loss when double cropped with pennycress (Phippen and Phippen, 2012).

Development of end uses, supply chains, and markets for pennycress

Pennycress oil has many promising commercial applications. It can provide a feedstock for biodiesel production (Moser, 2012), and can also be used as a source of biokerosene for "green" aviation fuel. Life-cycle analyses show that total greenhouse gas emissions and energy balance from these biofuels are considerably superior to equivalent fuels derived from fossil fuel sources (Fan et al., 2013). Pennycress oil also provides high-quality feedstocks for industrial lubricants (Cermak et al., 2013), and the seed meal remaining after oil extraction is high in protein, with potential use as a fodder supplement or a weed-suppressing horticultural biofumigant (Vaughn et al., 2005). Recent estimates of potential pennycress production in Midwest USA projected production of circa 4 billion US gallons on 16.2 million hectares (Fan et al., 2013). To expand to such a scale, much expansion will be needed in logistics and processing facilities and other aspects of post-production logistics. Additionally, a wide range of technical hurdles remains, including improving storage stability and performance at low temperatures, and increasing energy density to levels closer to diesel from fossil sources (Moser, 2012).

Complex problems for pennycress commercialization

Pennycress commercialization may be challenged by a range of issues that constitute complex problems. Ineffectively addressed, these issues may prevent pennycress from realizing its full potential to improve sustainability, and may also create barriers to investment in pennycress commercialization.

Impacts on regional land use and landscape

Extensive cultivation of pennycress could cause changes in the structure and function of agricultural landscapes, and may conflict with cultural values about those landscapes. These effects may affect key concerns of stakeholder groups quite differently, creating discord. In particular, pennycress cultivation may not be seen as an unalloyed benefit by sustainability-oriented stakeholders, such as environmental NGOs that are now strongly interested in agricultural practices. While widespread integration of pennycress into summer-annual crop production systems would certainly add diversity, it is possible that the net effect might be seen by these stakeholders as only an incremental improvement, involving a fallow-season "monoculture" of sorts. In addition, other potential effects of extensive pennycress cultivation that may arouse sustainability concerns include invasiveness, effects on pest dynamics, e.g., via by providing a winter host for diseases (Smith et al., 2011), and effects of possible increases in agrochemical inputs (Ray and Foley, 2013). For example, e.g., unintended effects on pollinators may result from neonicotinoid pesticide residues (Budge et al., 2015).

Use of new plant breeding technologies to improve pennycress

New plant breeding technologies are now being used in many crops (Hartung and Schiemann, 2014), and include methods such as genome editing, which induces precisely-targeted mutations, often without transfer of genes among organisms (Camacho et al., 2014). Concern about the use of these new breeding techniques is growing among sustainability-oriented stakeholders, and evidence from surveys suggests that the extensive public concerns about current GE crops may spread to crops produced by the new breeding techniques (Palmgren et al., 2015). If so, it is possible that rapid improvement of pennycress by use of these techniques will be curtailed by stakeholder objections. Currently, the new techniques are not being used to develop pennycress, but arguably may be necessary to achieve rapid and cost-effective development of high-performance germplasm.

Sustainability standards for production of pennycress products

Biofuels and other bio-based products made from pennycress may face sustainability concerns that have been expressed about other sources of liquid biofuels, e.g., corn-based ethanol (Dale et al., 2014). These concerns include effects on soil, water, biodiversity and land resources, life-cycle greenhouse gas emissions, and undesired socio-economic impacts. Production and post-production practices that meet stakeholder expectations for managing such effects can be codified via development of so-called sustainability standards. Efforts to develop sustainability standards for biofuels have been contentious (Boucher, 2012) and similar problems may arise around new feedstock crops such as pennycress.

Below, we describe the elements of the sustainable commercialization approach that we have implemented for pennycress.

An innovation platform for sustainable commercialization

Our approach addresses the complexity of sustainable commercialization by developing a so-called innovation platform (Kilelu et al., 2013; Ison et al., 2014) for pennycress commercialization. An innovation platform is an emerging organizational form that provides coordination among multiple groups of workers, in situations where each group is striving to develop innovative solutions to separate aspects of a complex problem (Ison et al., 2014). In our case (Figure 2), dedicated working groups are needed to address germplasm development, multifunctional agroecosystem design and management, and development of end uses, supply chains, and markets. Innovation platforms aim to stimulate coordinated and mutually-supportive innovation among such groups (Kilelu et al., 2013). For example, germplasm development can be coordinated with agroecosystem

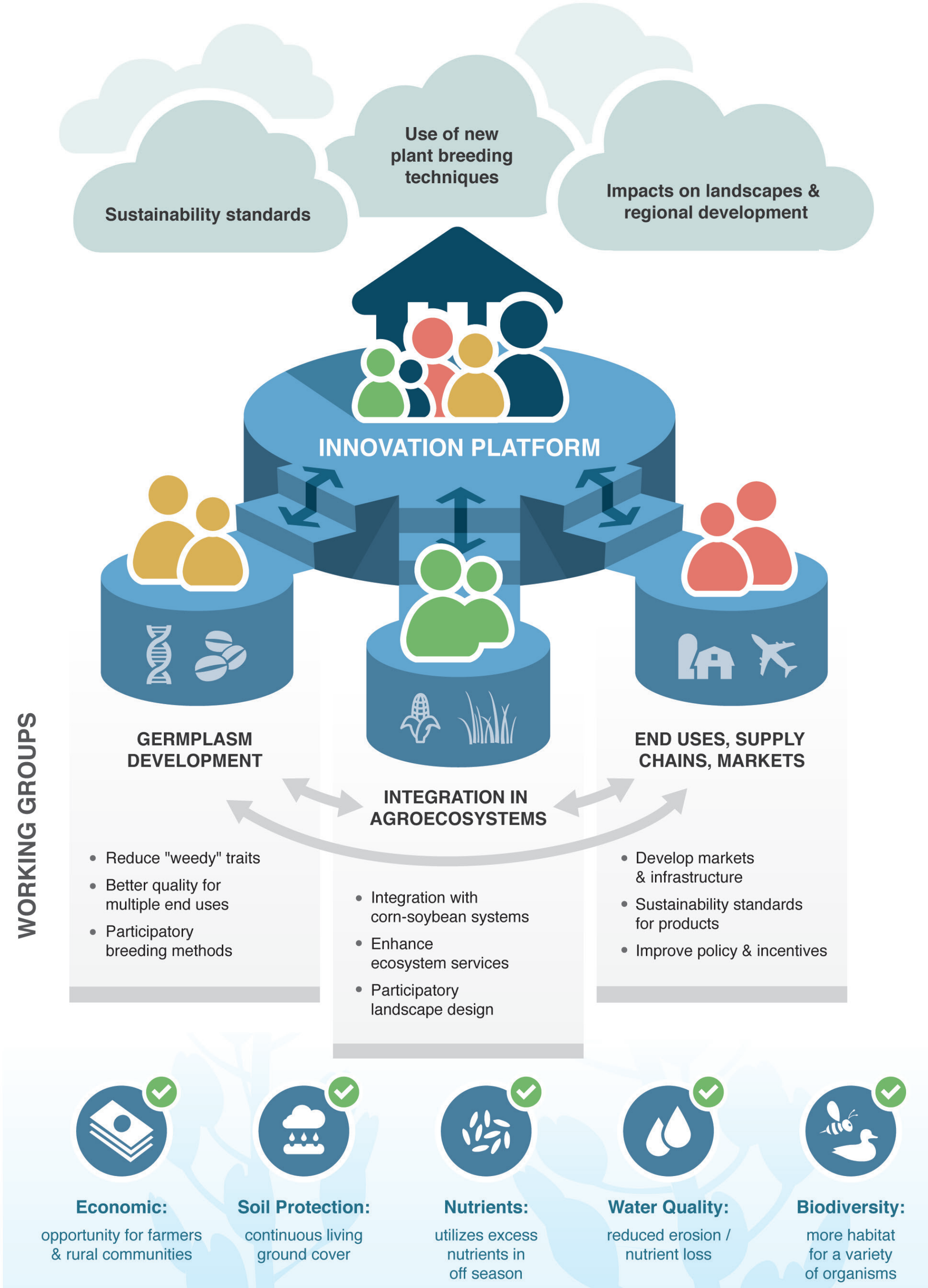

Figure 2

Organization of sustainable commercialization project for pennycress.

Project is built on three focused working groups for germplasm development, agroecosystem integration, and development of end uses, supply chains, and markets. An integrative innovation platform enables coordination and collective governance among working groups. Enhanced ecosystem services provide the foundation for the project; several complex problems are looming and will require management as commercialization proceeds.

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diversification and end-use development by identifying critical traits for diversification and end uses, and addressing complementarities and conflicts among such traits in germplasm development.

To address the complex nature of sustainable commercialization, an innovation platform must coordinate innovation that goes well beyond technical innovations in germplasm, agroecosystems, or end uses, supply chains and markets. Technological and technical innovations must be complemented by other levels of innovation (Leeuwis and Aarts, 2011; Peterson and Magers, 2011; Ison et al., 2014), including knowledge innovation (e.g., in human capacity for adaptive co-management of diversified and multifunctional agroecosystems), and innovations in social organization and relations (e.g., certification schemes to verify sustainability attributes). These levels of innovation—and coordination among them—will be critical to efficiently realizing the potential of pennycress products to have strong sustainability attributes.

Innovation platforms that support such comprehensive innovation directly address the complexity of sustainable commercialization, i.e., its multi-dimensionality, uncertainty, and diversely-defined nature. First, platforms engage a wide variety of stakeholders in collective efforts to characterize diversely-defined challenges that arise in sustainable commercialization, seeking to clarify the nature of these challenges and to identify opportunities for collective efforts to address them. Second, the multi-dimensionality of sustainable commercialization is addressed by drawing on a wide range of sources for knowledge relevant to this wide range of dimensions. Finally, platforms address unpredictability by engaging multiple stakeholders in ongoing, collective efforts to design, implement and coordinate innovation, assess outcomes of implementation, and take further action in response to these outcomes.

Coordination of innovation in the face of complexity requires that innovation platforms organize and facilitate a wide range of activities (Leeuwis and Aarts, 2011; Klerkx et al., 2012). In the case of pennycress, these include formation of visions, reflecting the views of a wide range of stakeholders, regarding how a new fallow-season crop could address sustainability challenges in a region. Innovators working on various aspects of pennycress commercialization must be convened, and the efforts of these innovators must be coordinated in the face of conflicting interests and divergent world views. Tension and conflict are inevitable and must be addressed, and differences in power among participants must be managed. Outcomes of innovation efforts must be assessed, and adaptive responses to changes in circumstances must be decided and implemented (Kilelu et al., 2013). In essence, the innovation platform helps the working groups achieve collective impact by facilitating systemic and strategic thinking about how to proceed with commercialization in a highly complex and competitive milieu (Westley et al., 2013), and about how to organize mutually interdependent activities.

In democratic societies, it essential to address issues of power in the functioning of the innovation platform, and in particular power imbalances between firms controlling supply chains, marketing and end uses and other actors. Imbalances may be reduced by emergence of new forms of relevant power. Essentially, sustainability-focused "non-consumption' stakeholders are gaining increasing power and influence over commercialization of new agricultural products (Peterson, 2009). These stakeholders do not have a particular interest in consumption of these products, but rather are concerned with sustainability attributes of products. This growing power results from developments in risk management and provision of capital to entrepreneurial firms interested in sustainable commercialization of novel crops such as pennycress, the growing significance of public acceptance to commercial success (Peterson, 2009) and the rise of powerful NGOs that can exert strong pressures on firms related to sustainability and social welfare issues (Snir, 2014). Increasingly, capital comes from investors strongly concerned with sustainability issues, societal impacts, and broad societal acceptance of investments. These include philanthropic foundations, such as the Gates and Buffett Foundations, or the rapidly growing number of "impact" investors, who seek to achieve social benefits in addition to financial gains (Kearney et al., 2014). Additionally, entrepreneurial firms may seek to appeal to markets concerned with sustainability attributes of products (e.g., sustainably-produced biobased products for the emerging agricultural bioeconomy (Chen and Zhang, 2015). These values-based capital sources and markets require firms to consider their reputations regarding sustainability, and the market viability of new products, and therefore incentivize entrepreneurs to be responsive to these considerations.

To develop innovation platforms, individuals and organizations that provide the necessary organization, facilitation, mediation, and capacity creation are critically needed (Klerkx et al., 2012; Hood et al., 2014). Recently, our pennycress project has received a grant of financial support for initial organization of an innovation platform. Now, we are in dialogue with a range of stakeholders to clarify key interests of each group around agricultural intensification and development of agriculture in general, and then exploring how pennycress is viewed in the light of these interests and concerns. These dialogues will to set the stage for dialogue and deliberation, in the innovation platform, about key sustainability attributes of pennycress and associated production systems and supply chains. Relevant groups include Union of Concerned Scientists, World Wildlife Federation, The Nature Conservancy, GreenAviation (*sic*), Iowa Soybean Association, Practical Farmers of Iowa, Minnesota Farmers Union, and a range of state and federal agencies.

A working group for integration of pennycress into regional agroecosystems

Ideally, extensive production of pennycress in a region will increase the multifunctionality of regional agroecosystems and landscapes by producing meaningful amounts of ecosystem services that are of high importance to farmers and other stakeholders, while imposing relatively small ecosystem "disservices" on these parties. It is unlikely that such an outcome will occur without intentional planning, design and innovation, as processes and phenomena across a range of spatial-temporal scales must be managed to achieve such a balance and range of services (Nassauer and Opdam, 2008).

To begin, an anticipatory planning effort (Quay, 2010; Guston, 2014) is called for. In such a process, a multi-stakeholder working group explores plausible scenarios for the future development of agriculture in the region (e.g., Atwell et al., 2010). These scenarios examine the effects of extensive cultivation of pennycress, in the context of multiple scenarios for regional agricultural development. The aim of this assessment process is to anticipate and avoid unintended and undesirable social and environmental impacts that have emerged as other crops have been developed and adopted (Carrasco et al., 2014). If extensive cultivation of pennycress were to occur in the region, what changes in structure, function, aesthetics, and cultural significance of agricultural landscapes would result? Would these effects, in net, help advance regional agriculture toward desirable future state(s)?

Participants should include, at a minimum, parties involved in agricultural production and supply chains, civil society organizations concerned with environmental and social effects of agriculture, research institutions, and government. Relevant methods include participatory scenario development (Johnson et al., 2012) and "narrative research" (Paschen and Ison, 2014). These methods have effectively promoted dialogue, learning, and collaboration in complex situations marked by widely-varying stakeholder perspectives (Selin, 2014).

If this anticipatory effort concludes that pennycress production would help advance regional agriculture towards a desirable future state(s), then emphasis can shift to innovation to enable profitable production of pennycress while also producing other ecosystem services of high value. Innovation may be needed to address a wide range of agronomic and agroecological challenges facing pennycress production. As an entirely new crop, there are many knowledge gaps concerning effective planting, harvesting, and fertility and water needs. To enhance ecosystem services related to continuous living cover, full and consistent stand establishment is crucial; current lines do not consistently achieve such establishment. To improve establishment, new management practices are being investigated that will allow pennycress to be planted by mid-September, a month or more before corn and soybean harvest (Gesch and Cermak, 2011). Management must also maintain adequate pennycress yields without unacceptable interference with subsequent crops. The effects of pennycress on spring soil temperature, water use, and weed management are not well established, and could create a complex mix of positive and negative effects on subsequent crops. Currently, a group of students, staff, and faculty at several universities are researching solutions to the production problems and knowledge gaps noted above, and an anticipatory planning effort is being organized with a range of stakeholder groups.

A working group for pennycress germplasm development

The pennycress germplasm being evaluated for development is essentially composed of previously uncultivated populations collected from many regions. Many current challenges of pennycress production result from "wild" traits of these ecotypes. Germplasm development aims to rapidly improve these traits. Such traits include variable rates of secondary seed dormancy; in non-cultivated populations, this trait helps maintain an ongoing seed bank. Such dormancy inhibits stand establishment, reducing yield and ecosystem service production. There is also considerable flowering-time variability, which reduces the potential for early harvesting and can delay development of subsequent crops. Additionally, seedpods shatter only a few weeks after maturity, which results in a narrow harvesting window and can result in large yield losses. Finally, pennycress seed contains levels of glucosinolate compounds that may be harmful to livestock (Moser et al., 2009).

Pennycress breeding and improvement programs are relatively new, with the first major breeding program being initiated at Western Illinois University, which has focused mainly on stand establishment and early flowering (Sedbrook et al., 2014). More recently, a working group for pennycress genomics and germplasm development has been established, coordinating efforts at the University of Minnesota, Western Illinois University, and Illinois State University. The working group aims to apply genomic technologies, such as DNA sequencing and targeted genome editing, to rapidly domesticate pennycress by improving undesirable traits as outlined above. We anticipate that the most problematic of these traits will be improved to agronomically acceptable levels within five years.

Pennycress genomics work is closely coupled with the needs of the breeding and agronomics programs, focusing on developing useful tools for pennycress breeders, and in turn, better germplasm for a variety of agronomic systems. To date, the first pennycress transcriptome (Dorn et al., 2013) and genome (Dorn et al., 2015) sequences have been released. These genomic resources are driving a mutation breeding approach to target the key traits previously mentioned, including ethyl methanesulfonate, fast neutron, and gamma ray mutagenesis. The goal is to identify new desirable phenotypes, as well as desirable mutations in key genes of interest. Pennycress is closely related to the model plant species *Arabidopsis thaliana*; thus, many of the lessons learned from the billions of dollars and decades spent on Arabidopsis research can now be directly applied to the development of this new crop species (Dorn et al., 2013, 2015; Sedbrook et al., 2014). With the genomic resources now in hand for pennycress, the use of new plant breeding technologies such as genome editing are feasible (Hartung and Schiemann, 2014; Sedbrook et al., 2014).

Release of commercially viable germplasm depends on progress on many traits, as noted above. As well, decisions must be made to identify desirable phenotypes for development of initial varieties. Given the relatively "unformed" phenotypes of pennycress, we are working with multiple stakeholder groups to expand the scale of this working group to engage a wide range of stakeholders, including producers, environmental groups, and end users. These efforts entail a deliberative exploration of costs, benefits and tradeoffs among alternative pennycress phenotypes and include a wide range of economic, environmental and social considerations. For example, current pennycress phenotypes are somewhat limited in nectar production; genomic work is identifying genes relevant to increasing production. If there are trade-offs between nectar production (and, potentially, support for pollinators in agricultural landscapes) and seed yield, how should these tradeoffs be addressed in germplasm development efforts? Another trade-off example relates to efforts underway to reduce glucosinolate content so as to make pennycress meal more palatable; this phenotypic change may compromise the biofumigant properties of pennycress. As well, the working group is exploring options for management of new pennycress germplasm as intellectual property, including the potential value of novel approaches such as "open source" distribution systems for plant mechanisms (Luby et al., 2015).

Conclusion

Sustainable commercialization, as we have framed it, is an ambitious and complex enterprise, requiring novel capacities. The innovation efforts of multiple working groups must be coordinated, and the larger purposes and outcomes of the resultant innovation must be collectively monitored, evaluated, and governed. An emerging organizational form, the innovation platform, appears to be a promising vehicle for such coordination and governance. These capacities for sustainable commercialization cannot be built quickly, but rather must be developed strategically. Rudimentary working groups have already formed around pennycress germplasm development, agroecosystem design and management, and development of end uses, supply chains, and markets. Coordination of these groups via an innovation platform is in an early stage. Therefore, a broad-based process of pennycress commercialization is underway, and is now striving to develop the capacities needed to implement the model of sustainable commercialization that we have described.

More broadly, the authors of this commentary are all contributing to the Forever Green Initiative's (Runck et al., 2014) effort to develop a portfolio of new fallow-season and perennial crops, and we see development of effective methods for sustainable commercialization as a crucially important product of the Initiative. Sustainability itself is arguably a capacity for ongoing learning and adaptation (Peterson, 2009). Therefore, initial experiments in sustainable commercialization must emphasize iterative and holistic evaluation of sustainable commercialization. These experiments also must emphasize ongoing collective and adaptive learning among the parties to the process. In this way, current approaches to commercialization can develop towards the ideal of sustainable commercialization.

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Contributions

- Contributed to conception of manuscript: KD, PE, AF, LF, JG, NJ, KH, BR, AW
- Contributed to drafting and revisions of text: KAA, KA, KD, PE, AF, LF, JG, GJ, NJ, KH, DM, WP, BR, JS, AW, DW, KW
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Competing interests

The authors have declared that no competing interests exist.