

Soil Health and Organic Farming

Plant Genetics: Plant Breeding and Variety Selection



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SOIL HEALTH AND ORGANIC FARMING

PLANT GENETICS: PLANT BREEDING AND VARIETY SELECTION

**An Analysis of USDA Organic Research and
Extension Initiative (OREI) and Organic
Transitions (ORG) Funded Research from 2002-2016**

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Introduction

Plant breeding and genetics can play an important role in building soil health. Most modern crop cultivars have been bred and selected to perform well in conventional farming systems over wide geographic ranges, and today's seed catalogues offer few regionally adapted cultivars suited to organic and low-input production systems (Figure 1). In recent years, several farmer-participatory plant breeding networks across the US have begun to address this critical unmet need.

Plant breeding and cultivar development conducted for and within the context of organic farming systems can lead to improved organic crop yields, and thereby facilitate adoption of organic practices that protect and build soil health. Breeding crops for the following traits may contribute directly to soil and water quality:

- Enhanced ability to utilize nitrogen (N) and other nutrients from organic sources.
- Enhanced symbiotic N fixation.
- Enhanced association with mycorrhizal fungi and other beneficial micro-organisms that assist nutrient uptake, promote tight nutrient cycling, and deter plant pathogens.
- Enhanced root biomass, depth, lateral spread, volume, exudation, and rhizodeposition, which build soil organic matter (SOM) throughout the soil profile.
- Increased above ground growth and cover (live plant and residue), which protect the soil surface and add organic matter.
- Increased weed tolerance and weed competitiveness through rapid emergence and establishment, tall or dense canopy, or other traits.
- Ability to establish, thrive, and yield in cover crop based conservation tillage systems.
- For cover crops: high biomass, weed suppression, effective N fixation or nutrient scavenging, winter hardiness, and ease of termination by mowing or roll-crimping.



Oregon State University

Figure 1. Researcher Bernadine Strik of Oregon State University with an organic blueberry trial, including a cultivar comparison of Duke (early season, moderate vigor) versus Liberty (late season, high vigor)

In addition to enhancing SOM and soil life directly, regionally adapted cultivars with these traits would reduce the need for tillage and cultivation for weed control, facilitate the use of cover crops, and reduce reliance on applied nutrients to maintain satisfactory yield and quality.

Challenges in Finding the Best Cultivars for Organic Production and Soil Health

Over the past 75 years, most plant breeding, field evaluation, and crop cultivar development have been conducted in the context of input-intensive conventional systems, in which crops are fed directly with soluble nitrogen (N), phosphorus (P), and potassium (K); and weeds, pests, and plant pathogens are controlled with synthetic crop protection chemicals. As a result, modern agronomic and vegetable crop varieties often give lower yields when grown organically with less soluble, biologically mediated nutrient sources, and without synthetic pesticides and herbicides (Hultengren et al., 2016). Organic growers must compensate for these genetic limitations with more tillage and cultivation for weed control, and increased application rates of manure and other organic nutrient sources—practices that can compromise soil health and water quality.

Organic and ecological production systems require crop cultivars adapted to specific environmental conditions (region, climate, soil, farming system), with strong resistance to prevalent pests and diseases (Hubbard and Zystro, 2016). Privatization of crop cultivar development and consolidation of the seed industry has led to the disappearance of many regionally adapted cultivars from seed catalogues, a loss that organic farmers cite as a barrier to successful production (Shelton and Tracy, 2016). Larger corporate seed businesses focus on “big” targets such as field corn or soybean for the entire US, and do not invest in minor crops, regionally adapted varieties, or breeding for organic production (van Bueren, 2016). Thus, organic farmers depend more on public university and non-profit NGO plant breeding programs for crop varieties better suited to their local regions and production systems.

The ongoing loss of public breeders exacerbates the problem. The majority of university plant breeders are approaching retirement age, and less than half are confident that they will be replaced. Thus, in addition to sustaining public breeding *per se*, an urgent need exists to “train the next generation of plant breeders” (Hubbard and Zystro, 2016).

Farmers can play an active role in meeting these challenges by conducting on farm variety trials and plant

breeding. Indeed, it is the world's farmers who have preserved, improved, and adapted seeds over the millennia. Farmer-participatory plant breeding (PPB), in which growers work with public plant breeders, is a highly effective and cost-efficient approach to developing new and improved public cultivars for organic production systems. Cultivars developed in the environment of their intended use are more likely to be well adapted thereto, and PPB engages farmers in all stages of the process, thereby aligning breeding goals and methods to farmer needs and promoting adoption and utilization of new releases (Hubbard and Zystro, 2016; Figure 2).

PPB faces several challenges, including the need for training and technical assistance to help farmers acquire breeding and seed production skills, including cultivar maintenance practices to maintain desired traits over generations of seed production (Zystro, 2016). In addition, breeding for organic systems requires a “systems” approach, as selection for single traits such as rooting depth or resistance to a specific pathogen may not yield the range of cultivar adaptation required (van Bueren, 2016). For example, tall growth habit and rapid canopy closure can enhance weed suppressiveness, yet may lead to more lodging or a more favorable environment for fungal pathogens, respectively. Thus, the entire organic plant breeding network finds itself on a learning curve regarding how to breed simultaneously for soil health, water quality, satisfactory yield and quality, and profitable organic production.

Another challenge is how to ensure adequate compensation for farmer-breeders to make on-farm cultivar development economically viable, yet keep new cultivars accessible without undue intellectual property rights (IPR) restrictions (Zystro, 2016). Already, the growing number of utility patents on crop cultivars or traits seriously limits farmer and public breeder access to crop germplasm. The Open Source Seed



Organic Seed Alliance

Figure 2. Researcher from the Organic Seed Alliance pollinating kale



Cultivars are most productive under the conditions for which they were bred.”
(Hultengren et al., 2016, p. 26)



Dozens of farmer-bred varieties are currently offered in organic seed catalogs.”
(Hubbard and Zystro, 2016, p. 25)

Initiative (OSSI) is building a “genetic commons” of crop germplasm that can never be privatized or patented, and will remain accessible to producers, breeders, researchers, and future generations in perpetuity (Spero, 2016). Farmer breeders must make a choice whether to support this endeavor by pledging their new cultivars as OSSI, or whether they need some degree of IPR protection such as Plant Variety Protection (PVP) to make their plant breeding and seed production activities economically viable.

Tips and Information Resources for Selecting Cultivars for Soil Health, Crop Yield and Quality in Organic Systems

Choosing the best crop cultivars for your organic farm can make an important contribution to the health of your soils, first by making it easier to farm sustainably, and second by building or protecting your soil directly.

Make the Best Use of What’s Available: Choosing from Existing Cultivars

Although seed industry consolidation has reduced options, there remains considerable latitude to select cultivars for organic production and soil health in your locale. This is especially true for vegetables and other specialty crops, with organic seeds of both heirloom and new varieties appearing in seed catalogues of many small to mid-size regional seed companies. Plant breeding and genetic conservation efforts in corn, soy, cereal grains, and other agronomic crops are beginning to expand choices for these crops as well. The following are a few tips for making the best choices from current crop varietal offerings:

- Source seeds close to home. Obtain seeds from local and regional seed growers, seed saver networks, and independent seed companies.
- Select cultivars adapted to your region, microclimate, and soils. Seed catalogues often give information on regional or soil type adaptation of their offerings.
- Buy organically or ecologically grown seeds whenever practical.
- Choose cultivars that have been bred, selected, and evaluated in organically managed fields and have performed well in organic systems.
- Choose cultivars with rapid emergence, seedling vigor, weed tolerance, drought tolerance, nutrient efficiency, and other key traits for organic production in your region.
- Consider cultivars described as having large canopy, tall stature, vigorous top growth, and/or deep, extensive root systems when these traits are compatible with your production system and market needs.
- Conduct side-by-side variety comparisons over several seasons to identify the best cultivars for your farm.

Sources of organically grown seed, regionally adapted cultivars, and cultivars suited for organic and ecological farming systems are included in Table 1, pg. 9.

Know What's Coming: Recent Advances and Improved Cultivars in the Pipeline

Farmer-participatory breeding and other research endeavors continue to develop promising new crop cultivars and breeding lines for organic production and soil health. Examples include wheat with improved weed competitiveness and N use efficiency (Jones et al., 2011; Worthington et al., 2015), soybean and dry bean with enhanced N fixation and deeper root systems (Heilig and Hill, 2014; Orf et al., 2016), grain corn with N efficiency and N fixation capacity (Goldstein, 2015), snow and snap pea with excellent emergence from cold soil (Myers et al., 2014), carrot lines that beat the weeds through rapid establishment and large canopy (Simon et al., 2016a), and enhanced “induced systemic resistance” responses in response to soil organisms in the tomato rhizosphere (Hoagland et al., 2016). While these new cultivars are not yet widely available, you may be able to obtain seed samples to try out on your farm.

- Visit organic plant breeding websites, such as Organic Seed Alliance and Northern Vegetable Improvement Collaborative to keep up with current developments.

- Contact university, NGO, or private breeders and seed growers to request samples of new cultivars or lines with priority traits for your operation.
- Even if a given cultivar or trait is not yet available to farmers, informing breeders, researchers, and organic seed advocates of your interest can help bring them to market.
- Some current developments to watch include (Table 1, pg. 9; Table 2, pg. 12):
 - N efficient/N fixing field corn – Mandaamin Institute (Table 2, item 3).
 - Improving heirloom dry beans through pure line selection (Table 2, item 13a).
 - Food grade soybean with rapid canopy closure (Table 2, item 13b).
 - Downy mildew resistant cucumber cultivars from Cornell, including DMR-NY264 DMR-NY401 and Martini and downy mildew resistant Trifecta melon. (Table 1, item 8b).
 - Downy mildew resistant butternut squash undergoing refinement; and currently available through Common Wealth Seeds (Table 1, item 8b).
 - Rice cultivar evaluation at Texas A&M University shows superior weed competitiveness in Rondo and Jasmine 85 (Table 2, item 14).
 - New quinoa varieties for organic production in Pacific Northwest, first releases expected within three years (Table 2, item 15).
 - Specialty food and malting barleys adapted to organic crop rotations in coastal Pacific Northwest (Table 2, item 15).

Up-to-date information on new crop cultivars and breeding advances can be found at many of the websites in Tables 1 and 2, pgs. 10 and 13. Some of these websites offer contact information to request seed samples or register your interest in specific new cultivars or traits.

Participate in Plant Breeding, Cultivar Evaluation, and Organic Seed Production

Plant breeding for sustainable organic production systems is in its infancy and the potential to enhance soil health and organic production through plant genetics remains largely untapped. The Organic Seed Alliance (OSA) seeks to realize this potential through research, networking, instructional materials for farmers on organic seed production and plant breeding, and dissemination of recent developments and new public cultivar releases (Figure 3). Several other NGOs, independent seed companies, and farmer-researcher participa-



Figure 3. Organic spinach grown in an Organic Seed Alliance breeding project

this vital endeavor by growing organic crop seed (a potentially profitable enterprise), conducting on-farm trials of cultivars and breeding lines, and breeding and selecting new cultivars. Many producers have successfully acquired the necessary skills to grow organic seed and improve crop genetics for organic systems to their own benefit and that of the entire organic sector. Examples of new cultivars developed primarily by farmers include Peacework bell pepper, Who Gets Kissed sweet corn (Figure 4), Solstice broccoli, the Seminole X Waltham advanced breeding line of butternut squash, and FBC Dylan wheat.

The following are some ways you can take part in developing the seeds for a future of healthy soils and successful organic production:

- Utilize available resources (OSA and other manuals, webinars, workshops, etc.) to learn the skills of organic seed production, seed saving, variety evaluation, and plant breeding.
- Save and select your own seed from your favorite cultivars.
 - Begin with seed not covered by patent or other

tory breeding networks are also actively engaged in plant breeding and public cultivar development for organic systems.

Farmers can participate in



More than 70% of the organic seed research projects conducted ... involved farmers. One researcher shared, 'We could not do this project without [farmer] involvement. Helpful is not a strong enough word. They are required partners.'"

(Hubbard and Zystro, 2016, p. 21)



I wish my work to be shared, not monopolized."

(Morton, 2016)



Figure 4. Who Gets Kissed sweet corn has excellent flavor and good emergence from cool soil, and was developed collaboratively by Dr. Bill Tracy and Dr. Adrienne Shelton of University of Wisconsin, Dr. John Navazio of Johnny's Selected Seeds, Jared Zystro of the Organic Seed Alliance, and Wisconsin farmer Martin Diffley.

intellectually property restrictions. Check seed tag and catalogue entry to verify that seed saving is permitted.

- The Open Source Seed Initiative (OSSI) affirms the four seed freedoms: to grow, share or sell, or trial and study seed; and to select, adapt, and breed new lines. OSSI pledged seed can be used for any purpose, the only requirement being that any progeny seed and any *new* variety or line developed wholly or in part from OSSI germplasm shall itself remain within OSSI.
 - Plant Variety Protection (PVP) allows seed saving for on-farm use but not resale.
 - Grow sufficient numbers of plants to maintain or enhance genetic base. Select best plants according to your criteria, and cull weak plants and off-types.
- Contract with an independent seed company to produce organic seed, evaluate new cultivars and breeding lines, or do plant breeding.
 - Participate in a USDA-funded or other network for organic plant breeding and seed production, to help develop the seeds of the future.
 - In on-farm trials, watch for individual plants, cultivars, or breeding lines that combine good yield and quality with potentially soil-enhancing traits such as weed competitiveness, nutrient efficiency, deep extensive root system, and overall vigor.
 - Keep good records of variety comparisons, experimental crosses, and other observations.
 - Share your findings with your network or project team, other growers and researchers, and the seed company or other source for your seed.

See Table 2, pg. 12, for resources for on-farm seed production, variety trialing, and plant breeding.

Table 1: Sources of Regionally Adapted, Organic, and Farmer-Selected Seeds

1. **Directory of Organic Seed Suppliers** National Sustainable Agriculture Information Service (ATTRA), https://attra.ncat.org/attra-pub/organic_seed/. Last updated in November, 2016.
2. **Over 100 Places to Buy Heirloom, Organic, and Non-GMO Seeds** posted by **Epic Gardening** at: <http://www.epicgardening.com/organic-heirloom-seed-companies-usa/>. Lists small and regional seed companies for all regions and the majority of states.
3. **Southern Organic Resource Guide: Sources of Organic and Non-GMO Seeds** <https://attra.ncat.org/sorg/seeds.html>.
4. **Organic Grain, Forage, and Cover Crop Seed Suppliers** (NCSU Extension) <https://organicgrains.ces.ncsu.edu/organicgrains-forage-and-cover-crop-seed-suppliers/>. Lists about 30 suppliers across the US.
5. **Seed Savers Exchange** <http://www.seedsavers.org/>. Established in 1975 to grow, share, and conserve heritage food crop seeds nationwide. Catalogue offers vegetable, herb, and flower seeds, including certified organic seed of 361 cultivars.
6. Some seed companies that emphasize regionally adapted, publicly available cultivars bred, developed, and produced on organic farms in the Northeast region include:
 - a. **Fedco Seeds** (ME) <https://www.fedcoseeds.com/>. *Vegetables, herbs, flowers, and grains; many organic and/or locally produced by individual farmers or small family businesses. Fedco is a partner in the Open Source Seed Initiative (OSSI).*
 - b. **Johnny's Selected Seeds** (ME) <http://www.johnnyseeds.com/>. *Vegetables, fruits, flowers, herbs, grains, and cover crops; some organic seed. Johnny's operates a 40 acre research, breeding and seed production farm where breeding lines are selected for vigor under low input organic systems.*

- c. **High Mowing Seeds** (VT) <https://www.highmowingseeds.com/>. 600 varieties of vegetables, herbs, flowers, and cover crops, all certified organic. Many are chosen for superior performance in organic systems, and bred, tested, and/or produced at their 40-acre research and seed production farm.
 - d. **Fruition Seeds** (NY) <http://www.fruitionseeds.com/>. 300 varieties of vegetables, herbs, and flowers; all certified organic, with emphasis on cultivars adapted to the short growing seasons of the Northeast. Seeds grown and selected in Finger Lakes region of New York, on three Fruition farm sites and by regional farmer network.
7. Some seed companies that emphasize regionally adapted, publicly available cultivars bred, developed, and produced on organic farms in the North Central region include:
- a. **Prairie Road Organic Seed** (ND). http://prairieroadorganic.co/Prairie_Road_Organic_Seed/Welcome.html. – Vegetables, flowers, garlic, All seed is certified organic and grown at their farm. Varieties developed at the farm are OSSl, and all varieties undergo continuous selection in organic conditions for vigor, hardiness, pest resistance, flavor, and other key traits.
 - b. **Baker Creek Heirloom Seeds** (MO) <http://www.rareseeds.com/>. Vegetables, flowers, small fruit.
 - c. **Nature and Nurture Seeds** (MI) <http://natureandnurtureseeds.com/>. Wide diversity of heirloom vegetables, sustainably grown, OSSl partner.
8. Some seed companies that emphasize regionally adapted, publicly available cultivars bred, developed, and produced on organic farms in the Southern region include:
- a. **Southern Exposure Seed Exchange** (VA) <https://www.southernexposure.com/>. 700 varieties of vegetables, flowers, herbs, grains, cover crops, and cotton grown by 50 farmers emphasizing but not limited to heirloom and other cultivars adapted to mid-Atlantic and southeastern US. Crop growing and seed saving guides.

- b. **Common Wealth Seed Growers** (VA) <http://commonwealthseeds.com/>. Comprised of a group of six farmers engaged in plant breeding, variety evaluation, and organic seed production for the mid-Atlantic and Southeast; catalogue offers 56 vegetable and herb cultivars.
 - c. **Sow True Seed** (NC) <http://sowtrueseed.com/>. Vegetable, herbs, flowers, and cover crops, emphasizing heirloom varieties and organically grown seeds.
9. Some seed companies that emphasize regionally adapted, publicly available cultivars bred, developed, and produced on organic farms in the Western region include:
- a. **Adaptive Seeds** (OR) <https://www.adaptiveseeds.com/>. Vegetables, flowers, herbs, garlic, grains, and cover crops. All seeds are public domain, open pollinated, and grown without agrochemicals on-farm or by network of Pacific Northwest seed growers; emphasis on “resilient, robust, productive” cultivars.
 - b. **Wild Garden Seed** (OR) <https://www.wildgardenseed.com/>. Vegetables, herbs, flowers; all organic seed; some cultivars developed on their Willamette Valley organic farm; some others selected for several generations at the farm.
 - c. **Territorial Seeds** (OR) <http://www.territorialseed.com/>. Vegetables, flowers, fruit, herbs; all certified organic, and all tested for vigor, quality, and regional adaptation (Pacific Northwest, west of Cascades) at their 75-acre research farm.
 - d. **Seeds of Change** (CA) <https://www.seedsofchange.com/Home.aspx>. Vegetables, flowers, herbs, trees, 100% certified organic, grown at the research farm and by network of certified organic growers.
 - e. **Sustainable Seed Company** (CA) <http://sustainableseedco.com/Organic-Seed/>. Organic vegetable, herb, and other seeds; vegetable seed farm certified organic in 2012.

Table 2. Resources and Networks for On-farm Organic Seed Production, Plant Breeding and Cultivar Selection for Organic Systems

1. **Organic Seed Alliance** <http://www.seedalliance.org/>, with upcoming events and links to regional networks, including Southeastern US at <https://seedalliance.org/southeast>. Publications page http://seedalliance.org/publications#publication_category_title_13 lists:
 - a. Participatory Plant Breeding Toolkit and other practical instructional materials for organic seed production, plant breeding, and cultivar evaluation
 - b. Results of recent plant breeding and variety trials
 - c. Proceedings of biennial Organic Seed Growers Conferences and regional summits
 - d. National State of Organic Seed reports (2011 and 2016).
2. **Student Organic Seed Symposium** <http://www.soseeds.org/> aims to develop a new generation of plant breeders and seed professionals to develop crops for organic and sustainable farming, and strengthen local and regional seed systems. Next annual symposium August 11-14, 2017 in Davis, CA.
3. **Mandaamin Institute** <http://www.mandaamin.org/> is breeding corn and wheat for optimum nutritional value for humans and livestock. High protein, N-efficient, N-fixing, and GMO pollen-excluding corn cultivars are under development. Website provides research updates and in-depth video presentations.
4. **Plant Breeding in Organic Farming Systems** eXtension web page, <http://articles.extension.org/pages/59457/plant-breeding-in-organic-farming-systems>. Also see *Seed Production and Breeding* in **eOrganic Webinar and Broadcast Recordings by Topic**, <http://articles.extension.org/pages/68066/eorganic-webinar-and-broadcast-recordings-by-topic>.
5. **Northern Organic Vegetable Improvement Collaborative (NOVIC)** <http://eorganic.info/novic/>. Farmer-breeder hubs in NY, OR, WA, and WI; manuals and other resources on organic plant breeding; a summary of crops and breeding objectives addressed in NOVIC II (OREI award in 2014).

6. **Organic Potato Project** <http://labs.russell.wisc.edu/organic-seed-potato/> University of Wisconsin scientists working with organic farmers to identify and select potato varieties that excel in organic systems. Variety trial results and instructions for field evaluation of plant vigor, weed competitiveness, pest and disease resistance, yield, and quality.
7. **Carrot Improvement for Organic Agriculture** <http://eorganic.info/group/7645>. OREI funded carrot breeding for seedling vigor, weed competitiveness, beneficial interaction with soil microbes, flavor, nutritional value, diverse colors, and other market traits.
8. **Organic Cucurbit Research: Critical Pest Management Challenges** <http://eorganic.info/cucurbits>. Includes plant breeding for disease resistance and vigor.
9. **Tomato Organic Management and Improvement Project** <http://eorganic.info/tomi>. Breeding and selecting tomato cultivars as part of organic tomato disease IPM.
10. **North Carolina State University – Organic Grain Production** including corn, soybean, and wheat variety trials: <https://organicgrains.ces.ncsu.edu/organicgrains-production/>.
11. **Northern New England Local Bread Wheat project** <https://extension.umaine.edu/localwheat/>. Results of organic wheat variety trials 2010-2013 at <https://extension.umaine.edu/localwheat/research/variety-trials/>.
12. **Value-Added Grains for Local and Regional Food Systems:** extensive variety trials of spelt, emmer, einkorn, and heritage wheats for organic production in NY, PA and ND.
 - a. 2014: http://orgprints.org/24148/1/24148-Kucekal-2014_01_09-1_MM.pdf.
 - b. Cornell, 2012-15 <https://plbrgen.cals.cornell.edu/research-extension/small-grains/cultivar-testing>.
 - c. North Dakota <https://www.ag.ndsu.edu/varietytrials>, click on crop at left.

13. University of Minnesota soybean and dry bean breeding program

- a. *Selecting “Modern” Heirloom Dry Beans*. Instructional webinar by T. Michaels. <http://articles.extension.org/pages/73846/selecting-modern-heirloom-dry-beans>.
- b. MN Agricultural Exp Sta. – new soybean cultivar to be released in near future.

14. Texas A& M University – IPM for organic rice, including cultivar evaluations

- a. Sustainable and Profitable Strategies for IPM in Southern Organic Rice, including regular project updates: <https://www.organic-center.org/our-projects/sustainable-and-profitable-strategies-for-ipm-in-southern-organic-rice/>.
- b. Video at <http://research.tamu.edu/2015/10/19/research-aims-to-help-growers-of-organic-rice-keep-pace-with-demand/>.

15. Washington State University – organic production, breeding, and variety evaluation of quinoa, wheat, barley, and other grains

- a. Kevin Murphy, assistant professor of barley and alternative crop breeding, <http://css.wsu.edu/people/faculty/kevin-murphy/>.
- b. *Quinoa: Improvement and Sustainable Production*, edited by Kevin Murphy and Janet Matanguihan. Purchase book at link from the above web site

16. US Testing Network of Practical Farmers of Iowa is a program to test public and private field corn germplasm, especially for the organic and non-GMO corn industry. <http://www.practicalfarmers.org/member-priorities/field-crops/us-testing-network/>.

17. The Experimental Farm Network is a nationwide non-profit open-source collaborative plant breeding network of over 300 growers, plant breeders, and researchers seeking to enhance food security and mitigate climate change. <http://experimentalfarmnetwork.org/>.

18. Northern Plains Sustainable Agriculture Society Farm Breeding Club <https://www.npsas.org/>, click on link for “Farm Breeding Club.”

Current Science on Plant Breeding and Genetics for Organic Production and Soil Health: An Analysis of USDA OREI and ORG Funded Research from 2002 - 2016

In the past 15 years, teams of university, non-profit, and farmer plant breeders have begun to address the need for new crop cultivars for organic systems. The USDA Organic Research and Extension Initiative (OREI) and Organic Transitions Program (ORG) have funded several farmer-participatory plant breeding networks that have released over 40 new public cultivars with traits important for organic producers, and generated hundreds of advanced breeding lines for additional cultivar development. Some of these new cultivars and breeding lines offer one or more of the soil health-enhancing traits noted earlier. In addition, some other OREI and ORG projects have provided valuable information on existing cultivars with better performance in organic systems and/or more desirable soil building traits.

Vegetable Crops

Many of the organic plant breeding efforts in vegetables have focused on resistance to various plant pathogens, flavor, nutritional value, and other market traits (Myers, 2016). However, selection traits have also included good cold germination and seedling vigor, weed competitiveness, and overall ability to yield in organic production systems. For example, the Northern Vegetable Improvement Collaborative has released one new cultivar each of snap pea, snow pea, and sweet corn with “excellent cold germination and emergence,” the two pea varieties also have tall vines (Myers et al., 2014).

The Carrot Improvement for Organic Agriculture (CIOA) project has



Strengthen organic crop seed systems, including ... plant breeding for organic production, with an emphasis on publically available releases. Breeding and selection characteristics for organic systems ... can include, but are not limited to: disease, weed, and pest resistance, stress tolerance, nutrient efficiency, performance in soil-improving and climate-friendly systems such as organic no-till, quality and yield improvement ... [and] cover crop breeding for enhanced performance in organic systems.”

(USDA NIFA, 2016)



Figure 5. Snow pea variety Ho Lan Dow identified in NOVIC project field trials as tops in flavor with excellent yield and disease resistance

collected and trialed carrot cultivars and breeding lines from around the world, and documented substantial genetic variation in germination rate, seedling vigor and canopy size (traits related to weed competitiveness), as well as disease and nematode resistance, flavor, and a diversity of colors (Simon et al., 2016a, 2016b, 2016c; Turner, 2015). Some Eurasian lines combine large canopy and resistance to *Alternaria* leaf blight (Simon et al., 2016a), which may help address this constraint on production of large-top varieties in humid climates. In multisite trials in the West (California and Washington) and Midwest (Indiana and Wisconsin), “[l]ines that emerged and formed a full canopy earlier than others resulted in the greatest crop yield in the presence of weeds as well as the greatest ability to suppress weed. [Thus,] selection of lines that favor early and full top canopy growth can be used as a low input, integrated weed management tool.” (Simon, 2016c). Having documented significant differences among locations and production systems (organic versus conventional) in active soil organic matter and microbiota, the research team is now analyzing variation among cultivars in endophytic and rhizosphere microbiota.

At least one seed company (Johnny’s Selected Seeds in Albion, Maine) is also breeding and selecting carrots and beets for seedling vigor and large tops, considered important for weed management and fresh market appeal (Haga et al., 2016)

Tomato breeding for organic producers has focused on horizontal (multi-gene and hence more stable) resistance to several major plant diseases (Myers, 2016; Hoagland et al., 2016). In addition to resistance genes *per se*, the project team is evaluating differences among breeding lines in responsiveness to two beneficial soil microbes—*Trichoderma harzianum* and *Pseudomonas fluorescens*—that induce systemic resis-

tance (ISR) to early blight (*Alternaria solani*), late blight (*Phytophthora infestans*), and gray mold (*Botrytis cinera*) (Hoagland et al., 2016). In California, tight nutrient cycling (in which bulk soil soluble N levels are low yet organic tomato crops obtain sufficient N via the activities of rhizosphere microbiota) was linked in part to the expression of genes related to N metabolism in tomato roots (Jackson, 2013). Thus, plant breeding to optimize plant root-microbe interaction can play a major role in co-management of soil health, plant nutrition, and plant diseases in organic crop production.

Cornell University breeders are working with farmers to develop improved winter squash, melon, and cucumber varieties for organic producers in the Northeast and Southeast, emphasizing resistance to the fungal disease downy mildew (DM, *Pseudoperonospora cubensis*) and cucumber beetle, which vectors bacterial wilt as well as causing feeding damage (Mazourek et al., 2016). The project has developed three new cucumber cultivars (DMR-NY264, DMR-NY401, and Martini) with moderate to high DM resistance and good vigor and yields, and one melon Trifecta which has “excelled” in trials. One of the project’s farmer participants in Virginia is doing extensive work on DM resistant butternut squash (*C. moschata*), based on crosses between standard butternut cultivars and highly vigorous and disease resistant tropical and warm-temperate pumpkins within this species (Frost, 2015). A successful cross between Seminole pumpkin and Waltham butternut has yielded an advanced (F6) breeding line of disease-resistant butternut with excellent flavor, which is undergoing refinement and is available in small quantities to growers (Common Wealth Seeds). While these breeding endeavors do not *directly* address soil health, nutrients, or weed tolerance, the new cultivars are characterized by large, vigorous vines and longer periods of active growth through DM resistance, with



All photos: University of Wisconsin—Madison

Figure 6. Potato varieties from the Organic Potato Project

better ground coverage and a potential for greater biomass and root exudate contributions to the soil.

The Organic Potato Project, a network of plant breeders and researchers at University of Wisconsin and organic farmers in the upper Midwest region evaluated 90 specialty and heirloom potato varieties on organic farms and developed practical information on organic seed potato production and conducting on-farm variety evaluations (Charkowski et al., 2013; Figure 6).

Fruit Crops

Most fruit crops are prone to pests and diseases and are therefore difficult to grow organically. Breeding new cultivars of fruit and other perennial crops requires a longer time commitment than cultivar development for annual crops like vegetables and grains. However, cultivar evaluations can identify selections among currently available fruit crop varieties that may be more suited to organic production. For example, researchers at Oregon State University have found that Marion blackberry utilizes soil moisture more efficiently and potentially requires less irrigation than the Black Diamond cultivar (Strik et al., 2014). The fruit of organically grown Marion also had significantly higher total soluble solids (an indicator of eating quality) than Black Diamond, which may compensate for the former variety's slightly lower yield. The same team is comparing two blueberry cultivars under organic production systems: the early maturing Duke and a more vigorous, late maturing cultivar, Liberty (Strik et al., 2015). Duke is considered fairly challenging to grow because it needs high soil fertility, and the researchers are investigating whether Liberty might have lower N requirements.

Cover Crops

Because cover crops play such a central role in maintaining and improving soil health, efforts to breed improved cultivars of cover crop species such as rye, hairy vetch, or buckwheat can make a direct contribution to healthy soils throughout agriculture. For example, in Minnesota, local land races of hairy vetch overwintered better (42-58% survival) and gave higher biomass and N than commercial seed produced in warmer parts of the North-Central region (2-12%) (Sheaffer et al., 2007). Fava bean strains also vary widely in cold tolerance, and four lines that are hardy to about 0°F have recently been registered (Landry, 2017). Thus, plant genetics may enhance winter survival, which is a major constraint on the use of winter annual legume cover crops in colder climates (Delate, 2013).

Variation in the genetics of the *Rhizobium* symbiont can affect N fixation efficacy in hairy vetch (Hu et al., 2015) and likely other legume cover crops; thus genetics of both plant and microbial symbiont may affect N fixation efficacy.

Genetic diversity in the form of interspecific mixtures is generally thought to contribute to the overall benefits of cover crops. One interesting finding is that, while multispecies mixes may or may not suppress weeds more effectively than single-species plantings, mixtures of several cultivars of a given cover crop (hairy vetch, winter pea, rye, wheat, or ryegrass) consistently enhanced weed suppression over single cultivar plantings in a multiple site-year study (Drinkwater and Walter, 2014). In another study, the summer annual grain tef, grown as a cover crop, showed significant varietal differences in ability to suppress Canada thistle; in this case, mixtures with soybean or sunflower outperformed the monoculture (Cardina et al., 2011).

Beginning in 2016, the OREI program specifically invited proposals for breeding cover crops for organic systems, and a USDA ARS team in Beltsville, Maryland received an award in 2015 to breed crimson clover, Austrian winter pea, and hairy vetch lines adapted to different regions (Mirsky, 2015). The four-year project will engage farmers in participatory breeding in North Carolina, Maryland, New York, and Washington, selecting for autumn establishment, winter survival, spring biomass production, N fixation, desirable flowering date, and ease of mechanical no-till termination.

Wheat and Other Cereal Grains

Farmers across the US have identified several breeding priorities related to challenges in organic cereal grain production: nutrient use efficiency especially N, weed management, disease resistance, and milling/baking quality (protein) (Brouwer and Colley, 2016; Kucek and Sorrells, 2016; Mallory, 2014; Shapiro et al., 2010). Breeding to enhance the wheat plant's ability to obtain sufficient N from organically managed soils with variable soil nutrient profiles can contribute to higher and more consistent grain protein percentages (Pate, 2016), a potential win-win for soil health and end-use grain quality.

A Washington State University team developed 20 advanced wheat breeding lines that performed well in organic production in the Pacific Northwest. The team has released germplasm for use in other public wheat breeding programs across the US (Jones et al., 2011). Cultivars and breeding lines showed considerable

genetic variation in “weed suppressive ability” (assessed as weed biomass), part of which was attributable to plant height and coleoptile length (Murphy et al., 2008). While plant height was directly related to yield, the coleoptile length trait appeared to entail a yield cost. Trials at two sites within the Pacific Northwest indicated a potential to breed and select wheat for N use efficiency (Dawson et al., 2011) and overall performance under organic management in this region (Murphy et al., 2007). Results of wheat variety trials in northern coastal California have been posted online (Organic Seed Alliance, 2013).

Washington State University researchers are also breeding and selecting barley for coastal region organic farmers who grow vegetable and other specialty crops, and use cereal grains to break pest, weed, and disease life cycles, and restore soil after intensive production. Breeding objectives include weed competitiveness, disease tolerance, and input efficiency as well as yield and quality in high-market-value specialty cultivars (malting barleys and colored, hulless food barleys with high antioxidant contents) (Meints et al., 2016). Making the cereal grain phase of the rotation pay for itself through specialty grain markets can enhance adoption of this soil health-enhancing practice by specialty crop producers. Researchers have released two new hulless food barley cultivars. One cultivar is named Havener, and 6000 pounds of it are being grown in 2017 that will provide seed for growers in 2018 (Murphy, 2017). The second variety release occurred in March of 2017. These cultivars were selected for high levels of beta glucan, broad adaptation, novel baking characteristics, and drought tolerance (Murphy, 2017).

University of Nebraska has expanded its wheat breeding program to address needs identified by organic wheat producers, including nutrient efficiency, yield, quality, and weed, pest, and disease resistance (Shapiro et al., 2010). The team evaluated 56 cultivars and some 1,500 breeding lines for performance in organic systems, and promising lines were further evaluated during 2010-13 for weed competitiveness in SD and overall performance in Iowa, New Hampshire, Vermont, and Maine (Baenziger et al., 2012).

In North Carolina, studies of over 50 winter wheat cultivars and breeding lines revealed substantial genetic variation in both allelopathic activity and weed-competitive growth habit. In field trials, weed suppression and tolerance of grain yield to weeds correlated with competitive but not allelopathic traits (Worthington et al., 2014). Weed suppressive genotypes were characterized by high vigor during tillering and heading, erect growth habit, high leaf area index (LAI), early heading date, and tall height throughout the growing season and at maturity (Worthington et al., 2015). Variety trial results are

posted online (North Carolina State University, 2016).

Cornell researchers are working with farmers in the Northeast to select breeding lines for seedling vigor and leaf width at the 3-5 leaf stage, seed size, and mature plant height (Kucek and Sorrells, 2016). Plant height is highly heritable, and all three parameters correlate with competitiveness against weeds. In addition to modern wheat cultivars, the team is evaluating emmer, einkorn, and spelt in New York and also North Dakota (Sorrells et al., 2016)

In southwest Michigan, experimental perennial wheat lines developed three times as much root biomass as standard annual wheat, and reduced nitrate leaching virtually to zero (Snapp and Swinton, 2013). The perennial grain also enhanced active soil organic carbon (C), soil enzymatic activity, and nematode communities. Although the experimental lines did not overwinter reliably and grain yields were only about 50% of standard annual wheat, their potential to enhance soil health, nutrient efficiency, and water quality merit further breeding efforts to improve agronomic performance. Farmer participants in the project team worked with Organic Seed Alliance to develop a Participatory Plant Breeding Toolkit (Ibid.).

Researchers in Nebraska (Shapiro et al., 2010), Utah (Creech et al., 2015), and Maine (Mallory et al., 2014) are integrating variety selection with other practices to improve organic wheat production. In Utah, four varieties and six advanced breeding lines will be evaluated with various compost and cover crop treatments (Creech et al., 2015), and the Northern New England Local Bread Wheat project (<https://extension.umaine.edu/localwheat/>) conducted extensive wheat variety trials during 2010-13 to identify cultivars best suited to organic production in the Northeast (Mallory et al., 2014).

Field Corn

In the Midwest, USDA Agricultural Research Service is working with farmers and the Mandaamin Institute to develop field corn varieties suited to organic systems. Target traits include N use efficiency, weed tolerance, disease resistance, and ability to exclude GMO pollen through gametophytic incompatibility (Scott, 2015). Breeding materials include land races from Mexico and South America that demonstrate high N use efficiency and a capacity to derive up to 50% of their N through fixation by rhizosphere or endophytic diazotrophic (N fixing) bacteria such as *Azospirillum*. The team has made substantial progress toward transferring



Figure 7a. A standard variety of field corn grown on a low-fertility tropical soil shows nutrient deficiency stress (left) while Mandaamin Institute's N-efficient field corn maintains vigor.

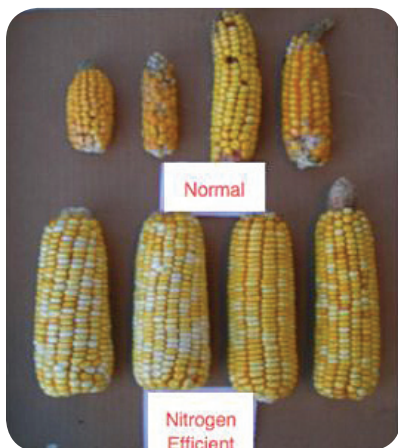


Figure 7b. Ears harvested from standard (top) and N-efficient (bottom) corn grown on soil low in N

these traits into standard Corn Belt inbreds or hybrids, and selection in organically managed soils low in soluble N has led to new breeding lines that give competitive yields in these conditions (Goldstein, 2015, Figure 7a). Plant genetics and gene expression regulate interactions of corn roots with a diversity of diazotrophs, other bacteria, and fungi that mediate plant nutrient uptake, disease resistance, and overall vigor (Goldstein, 2016). A long history of corn breeding in conventional farming systems with liberal use of soluble N fertilizer has apparently led to an increase in *Fusarium* spp. in the rhizosphere, which, while not directly pathogenic, may deter diazotrophs and render the crop more dependent on soluble N. Conversely, breeding and selecting corn in organically managed soils with lower levels of soluble N can restore and strengthen beneficial root-microbe relations, and enhance N fixation and nutrient efficiency.

In addition to competitive grain yields in low-N soils, some of the new corn lines developed at Mandaamin Institute show enhanced drought tolerance and increased protein percentage with a high methionine content, an important trait for organic poultry and livestock feed (Goldstein, 2015). Cultivars with these traits would reduce dependence of corn production on soluble N, and protect water quality, soil organic matter, and soil health, which can be compromised by heavy N inputs. They would also reduce production costs, facilitate adoption of organic practices for agronomic crop rotations that include corn, and even organic poultry and livestock production.

Soybean and Dry Bean

Weed management and crop nutrition have also emerged as top priority traits for organic soybean and dry bean production, with a specific

focus on efficacy of the legume-rhizobia symbiosis in N fixation.

Dry common beans (*Phaseolus vulgaris*, including kidney, navy, pinto, black, cranberry, great northern, and other types) are generally not strong N fixers, with only 10-20% of their N derived from the atmosphere (%Nd_{fa}) in organic field trials in Michigan (Heilig and Hill, 2014). Breeders have developed several lines with 40-50 %Nd_{fa} by crossing a standard black bean cultivar (Zorro) with a higher N-fixing Mexican land race (Puebla-152), and have located genes related to symbiotic N fixation on several chromosomes, in proximity with other genes regulating seed yield, plant biomass, and root mass.

University of Minnesota breeders are working with farmers to evaluate and improve dry bean cultivars for organic production in the Midwest, and are breeding and selecting new lines with vigorous root systems, root rot resistance, and enhanced N fixation (Orf et al., 2016). Small-seeded market varieties (black, navy, pinto) yielded most reliably for organic producers, yet several heirloom varieties (Jacob's Cattle Gold, Lina Sisco's Bird Egg (Figure 8), Peregrine, and Tiger's Eye) showed promise for improvement through a simple pure line field selection method readily learned and implemented by farmers and gardeners (Michaels, 2016). Seed increase for regional organic producers is now underway.

The University of Minnesota research team has also developed several new soybean lines with early vigor and rapid canopy closure (weed competitiveness) that will undergo yield trials in 2017. One of these is a large-seeded, yellow-hilum, high-protein line that has been proposed for seed increase and release through the Minnesota Agricultural Experiment Station as a food grade soybean for organic producers (Orf, 2016). The team is also comparing the N fixing efficacy of field-collect-



Seed Savers Exchange

Figure 8. Lina Sisco's Bird Egg

ed and commercial rhizobia strains for soybean and dry bean.

In North Carolina, soybean breeders identified seed size as a heritable characteristic related to weed competitiveness. Larger seeded types showed greater early season vigor, faster canopy closure, and lower weed biomass seven weeks after planting, while small seeded, narrow-leaf natto types were poor competitors (Place et al., 2011a, 2011b).

Other Field Crops

An organic rice production study in Texas, initiated under a 2015 OREI award, includes evaluation of 20 cultivars and breeding lines in preparation for breeding efforts. Significant differences in weed suppression were documented, with two cultivars (Rondo and Jasmine 85) showing the best stand establishment and greatest weed suppression, as well as resistance to the rice disease narrow brown leaf spot (Zhou, 2016).

Washington State University is breeding and evaluating quinoa cultivars for organic production, with multiple goals including drought and salinity tolerance, N use efficiency, and pest resistance as well as yield and other agronomic and marketing traits (Murphy, 2013). Substantial progress has been made, and breeders expect to release at least one Washington State University quinoa cultivar within three years (Weaver, 2016).

Some General Topics in Organic Plant Breeding Research

Breeding crops for sustainable and organic production requires a systems approach that considers crop resilience to varying conditions including climate change, and capacity to contribute to soil health and other ecosystem services, as well as satisfactory yield and market qualities (van Buren, 2016). Narrow focus on single traits may not yield varieties with improved overall performance in organic systems. For example, selecting for larger root mass to enhance drought tolerance may not be as effective as selecting more broadly for multiple mechanisms of stress tolerance, including flexible root architecture and function in response to specific stresses. Such “systems” breeding may need to include consideration of traits like root and above-ground residue return to the soil to build soil health and water holding capacity, and even improved floral structure for insect pollination in legumes to ensure their agronomic and ecological functions (van Bueren, 2016).

Another key to resiliency is to broaden the focus of plant breeding efforts to include traditional food plants

that have fallen out of mainstream use, especially perennial species (Dawson, 2016). As noted above in the specific case of cereal grains, perennial crops can greatly enhance soil health through larger root mass, better nutrient cycling, and greatly reduced need for tillage and cultivation.

In a recent survey of farmers, a majority considered breeding for organic systems important to successful organic farming, and one in four expressed interest in “on-farm plant breeding regardless of whether there is economic opportunity” (Hubbard and Zystro, 2016). Farmer participation gives plant breeders an opportunity to do the breeding in realistic on-farm conditions. Because organic farming systems present more variable conditions (soils, nutrients, microclimates, disease pressure, etc.) than conventional systems, farmer involvement may be especially important for developing cultivars for organic systems. Furthermore, farmers evaluating germplasm in their own fields can more readily identify plants that are outstanding due to genetics rather than site- or soil-related variation (Hubbard and Zystro, 2016).

Farmer-based variety trial networks have expanded considerably in the past five years, thanks in part to OREI funded projects. Other endeavors include Practical Farmers of Iowa’s US Testing Network, and networks in the Pacific Northwest (vegetables), Montana (vegetables), and California (wheat and vegetables), and a new national Experimental Farm Network (Hubbard and Zystro, 2016). However, further efforts to “expand and strengthen systems for simplified and fairly compensated on-farm variety trials” are needed (Hultengren et al., 2016).

During 2016, two regional summits convened to identify organic producers’ current plant breeding priorities. In addition to crop yield, nutritional value and other market qualities, Pacific Northwest organic farmers and plant breeders identified a number of breeding priorities that relate to soil health (Brouwer and Colley, 2016). These include:

- Disease resistance (across crops)
- Beneficial microbial associations (across crops)
- Adaptation for diverse crop rotations (cereal grains, field corn)
- Enhanced root traits (cereal grains, tomato grafting rootstocks)
- Perennial and forage growth habit (cereal grains)
- Carbon sequestration and adaptation to organic no-till (cereal grains)

- Nutrient use efficiency, especially N (field corn, cereal grains, sweet corn, potato, brassicas, tomato family, spinach)
- N fixation (legumes)
- Water use efficiency (sweet corn)
- Early emergence and seedling vigor (field and sweet corn, tomato, spinach)
- Weed competitiveness (legumes, carrots)
- Better crops for improving soil health and resiliency (cover crops)

In summary, “we need to breed smarter plants that can meet the needs of organic farmers in the Pacific Northwest and better adapt to our changing climate” (Kim Leval, quoted in Brouwer and Colley, 2016).

A plant breeding needs assessment for organic vegetable growers in the Northeast identified pest and disease resistance, and heat, cold, and frost tolerance as top priorities, as well as an overall need for varieties specifically bred and selected to excel under organic management (Hultengren et al., 2016). Weed tolerance was specifically mentioned only once, as a breeding priority for pepper. Working group recommendations included a greater emphasis on regionally adapted cultivars specifically for organic production in the Northeast.

Questions for Further Research in Plant Breeding and Genetics for Soil Health: An Analysis of USDA OREI and ORG Funded Research from 2002 - 2016

Important strides have been made toward improving crop germplasm for sustainable organic production systems. In addition to cultivars already released, hundreds of breeding lines with key traits represent a potential to provide organic farmers with a much wider range of food crop cultivars that perform well and contribute to soil health. Realizing this potential will require a long term commitment to plant breeding and research. Some general topics include:

- How can adequate infrastructure for organic plant breeding be secured for the long-term? This includes stable funding, plant breeding expertise, networking, and farmer training.
- How can plant breeders (including farmers) be remunerated fairly without restricting others’ freedom to grow, share, and trial seed, or use seed to develop new cultivars?

- How can plant traits relevant to soil health be identified, characterized, and selected in ways compatible or synergistic with crop yield, yield stability, and market qualities?
- How can the “systems” approach to plant breeding and selection be refined to optimally address multiple production, quality, plant protection, soil health, and other objectives?
- How can practical, low-tech, on-farm field methods of plant breeding and selection be designed or fine-tuned for rapid, cost effective crop improvement for organic systems?

Some specific topics that merit further plant breeding and research for soil health include:

- Genetics of plant-soil-microbe interactions, and suites of plant traits that optimize interactions with beneficial soil biota, including:
 - N fixation.
 - Nutrient uptake efficiency, tight nutrient cycling.
 - Disease suppression or disease resistance.
 - Tolerance to drought, heat, cold, and other abiotic stresses.
- Nutrient use efficiency in a wider range of crops, especially crucifers and other heavy N-feeder vegetables.
- Enhanced N fixation in dry bean and other legumes.
- Weed tolerance and weed competitiveness in a wider range of crops:
 - Characterization of key heritable traits responsible for weed suppression or yield tolerance (plant height, canopy density, root mass and architecture, etc).
 - Role of allelopathy in genetically-modulated weed suppression in field conditions.
 - Potential yield or soil health tradeoffs related to allelopathy and other weed-suppression traits.
- Plant characteristics that contribute directly to soil health (high biomass, heavy residue, deep, extensive root systems, root exudates, etc.), and how these can be selected in a way that is compatible or synergistic with crop yield and desired market qualities.
- Improved cover crops for organic systems, including N fixation, biomass production, early establishment, weed and disease suppression, and ease of mechanical no-till termination.

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* For project proposal summaries, progress and final reports for USDA funded Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) projects, enter proposal number under “Grant No” and click “Search” on the CRIS Assisted Search Page at:

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Notes



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