Technological Trajectories in Plant Breeding: Constraints to Breeding for Sustainable Agriculture In Europe and Scandinavia

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Introduction

The industrialization of farming practices in the last two centuries has led to dramatic increases in global output, most recently as a result of greater inputs of fertilizer, water, pesticides, new crop strains, and other technologies of the 'Green Revolution' (WHO, 1990). Yet this rise in productivity has not come without cost. Since the publication of Rachel Carson's *Silent Spring* in 1962, conventional agriculture has faced an ongoing critique of its long-term effects on human health and the environment, and is so energetically and chemically intensive it is now widely accepted to be unsustainable (Tilman, 1999). The production of inorganic nitrogen fertilizer is highly energy intensive, is based on nonrenewable natural gas resources, and generates N_2O and CO_2 emissions. Its use in agriculture also generates N_2O and has led to the eutrophication of lakes and streams, as well as groundwater contamination. Global supplies of phosphorous, mined from nonrenewable phosphate rock in an extremely polluting process, are predicted to peak in 2033 (Craswell et al., 2010). Run-off and leaching of surplus phosphorous is damaging to groundwater and surface waters. Intensive tillage practices have compounded environmental degradation due to erosion, soil compaction, and loss of soil fertility and topsoil (Montgomery, 2007). Widespread monoculture and crop genetic uniformity have led to severe declines in biodiversity (Hole et al., 2005), ecosystem instability (Tilman et al., 2006), and an increasingly chemically intensive battle against crop diseases, pests and weeds (Johal and Huber, 2009).

Water scarcity is an additional factor that is predicted to constrain agricultural production in the future (Rosegrant et al., 2009). A portion of the yield gains achieved following the Green Revolution was due to irrigation, and to cultivars that responded well to moist, high-nutrient conditions. Unsustainable use of water resources for irrigation has led to depletion of groundwater and river basins in many parts of the world. As environmental degradation continues and the costs and competition for water increase, one of the prime bases for high-yield agriculture is at risk. "Without assured supplies of water, high-tech agriculture, certainly as it has evolved over the last half century, is not an economic proposition, at least not outside the temperate zone" (Marglin, 1996).

High-input agriculture (HIA) is also heavily concentrated at multiple social and economic scales, and is characterized by strong power imbalances which have adverse consequences for smaller farmers and for communities. A consensus has emerged that the negative environmental and social side-effects of conventional agriculture need to be reduced. The metrics of improvement are often framed in terms of *sustainability*, a concept defined in terms of environmental, economic, and sociocultural stability; in fact, Bell and Morse (2008) argue, the critique of HIA has been influential in the evolution of the concept itself. Sustainability applied specifically to farming practice leads to a definition of agriculture that conserves resources for future generations, is economically viable, and promotes social equity (cf. Francis and Calloway, 1993; Thompson and Scoones, 2009). Such a system relies on knowledge, ecological principles, and optimum social and biological diversity, an approach many define as "agroecology."[1]

The high-yielding plant variety (HYV) is a pivotal cog in the machine of HIA; because it is so tightly coupled with other components of the system, it has been considered an important vector for the transfer of other system technologies (McGuire, 2005; Bonneuil, 2008). Chemical inputs in particular are embedded throughout the agricultural research, selection and trialing process (Maat, 2011). "Agricultural research

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[1] *The term *agroecology* has been interpreted differently by numerous authors. Francis et al. (2003) have defined it broadly to mean the ecology of food systems, as a means for evaluating the health and sustainability of food systems more holistically than through traditional neoclassical economics. Likewise Dalgaard et al. (2003) have defined it as the multidisciplinary study of the interactions between plants, animals, and humans within agricultural systems, one which considers farming's social, cultural, and economic contexts. While this thesis employs a systems approach to study linkages within food production systems, in the context of exploring technological trajectories I use *agroecology* more narrowly to describe a holistic technological paradigm and set of practices that relies on the science of ecology to exploit agroecosystem interactions; in other words, the science and application of cultural methods of farming with the aim of sustainable yields, efficient nutrient and energy cycling, optimized biodiversity, reduced off-farm inputs and pollution, and equitable farm income. This includes a diverse range of practices such as crop rotations, use of crop residues, biological pest control, composting, legumes, agroforestry, intercropping, and genetically diverse crop mixtures. Although not synonymous with agroecology, "organic," "biodynamic", "natural," "low-input" and "indigenous agriculture" are examples of farming systems practiced throughout the world that can be said to incorporate agroecological principles to different degrees.

has evolved within, and helped shape, a breeding-chemical-mechanization techno-economic mode, in which genetics-based breeding activity is integrated with the development and use of synthetic chemical fertilizers and pesticides, and new machinery" (Hogg, 2000). Limits to input use are becoming widespread in Western Europe, and European member states must now define codes of Good Agricultural Practice, often including standards for reduced application of N, P, and pesticides; reducing dependency on off-farm inputs has socioeconomic benefits as well, as it increases farmers' profit margins. However, although orthodox breeding science has argued that HYVs selected under nutrient-rich conditions outperform unimproved varieties in all environments, calls for reduced inputs are not likely practicable without specific breeding approaches aimed at more genetically diverse systems.

One aspect of the campaign for more sustainable food systems is the return to the "local" (Hinrichs, 2003). But just as plant breeding science is a less visible aspect of the agricultural system, likewise structural changes in the seed industry have important but often less visible consequences for local food production and, furthermore, for regional food security and seed sovereignty. Consolidation and vertical integration in agribusiness have resulted in concentrated production of seed in just a few areas. So while many cereals and vegetables may be increasingly "locally grown", the seeds for these crops are nevertheless selected and bred under very specific, high-input conditions in a few regions. For example, while spinach seed was once bred in several different bioregions in the US, today all breeding work for the entire US spinach industry (and much of the world) is targeted for growers in Salinas Valley, California, and Yuma, Arizona (Peters, 2010). Cultivars selected and developed in these nuclear centers are no longer adapted to a diversity of growing environments, and finding cultivars adapted to local conditions—for example with less water or fewer soil nutrients—is increasingly difficult for farmers (Peters, 2010). The monopoly of the seed industry by a few large players has also led to the appropriation of genetic resources (Kloppenburg, 2010), not to mention a breeding focus dominated by fewer and fewer high-value commodity crops, such as maize, wheat and soy, at the expense of local staples or more diverse markets with lower profit potential (Hogg, 2000). The diversity of cultivars and crops that do not possess the traits valued by large scale industrialized agriculture are neglected; thus the countless varieties that possess quality traits valuable to smaller-scale producers fall increasingly out of use, crop diversity continues to decline, and more and more material is relegated to gene banks for posterity.

It has been forty years since Adams et al. (1971) observed that "genetic and/or cytoplasmic uniformity in widely grown economic plants render them particularly vulnerable to disease epidemics," yet plant breeding research and development continues to target monoculture systems, provoking the need for more chemical crop protection. Francis and Smith (1985) have argued previously for the development of cultivars for mixed cropping systems, stating simply that "genetic improvement for these systems has not been done". In last decade breeding for more diverse, low-input cropping systems has emerged as a research priority in European agriculture, with the formation of the European Consortium for Organic Plant Breeding (ECO-PB). Diversifying crop systems in time and space can be achieved using a number of traditional methods such as yearly rotations, mixed populations, intercropping of species and multilines, shifting cultivation; but the complexity of variables in multi-crop systems implies a more complex research framework. Given the high investment costs and long-term process of plant selection (typically 10-15 years), contemporary conventional breeding is thus committing farmers, food systems, and the environment to further degradation for generations to come.

Research Objectives

This study aims to contribute to an understanding of the mechanisms underlying technological trajectories in plant breeding. It specifically investigates the potential role of individual plant breeders, markets, institutions and scientific and technological paradigms in locking-in plant breeding to high-input environments. For example it asks:

- What is the extent of conventional breeders' awareness of low-input systems and agroecological methods? What is their degree of agency in choosing breeding objectives and methods?
- What is the role of the European seed system in reinforcing prevailing science technology, and excluding alternatives?
- How are plant breeding trajectories linked with agroecosystems and institutions?
- Are modern high-yielding cultivars sustainable? On what basis?
- What shifts might be necessary in order to support breeding for more sustainable cropping systems?

Methods

This study takes an interdisciplinary, intuitive, and qualitative approach to these questions. Building on a foundation of studies in social science (food systems, systems theory, anthropology) and life science (botany, plant ecology, seed science, genetics, plant breeding), I reviewed a broad base of literature on technological change in agriculture, and specifically the history of technological change in plant breeding science. With this theoretical framework in mind, I began a survey of wheat breeders at the main private cereal breeding companies in Scandinavia. While my original aim was to get a quantitative picture of breeders' individual technological choices, what quickly emerged from these interviews was a more complex reality of interactions between individual and institutional processes. I decided a more compelling line of study would be to shift gears and investigate the features of the formal seed system in the European Union, their epistemological bases, their interactions, and ultimately, their impact on the potential for breeding for more sustainable systems.

I located subsequent farmers, researchers and historians using a *de proche en proche* method ("friends of friends", Blanchet and Gotman, 2001), with the purpose of interviewing influential stakeholders rather than a statistically representative sample. Thanks in part to the consolidation of the seed industry in the last several decades, the number of key stakeholders in wheat breeding in this region is fairly small, and they are often professionally acquainted with one another—even if they disagree scientifically.

With this thesis I therefore attempt a nonlinear, "narrative" synthesis of data from several sources: 1) an analytically (but not statistically) representative sample of commercial wheat breeders; 2) a review of natural and social science literature on technological change in plant breeding, and relevant national and EU policy documents; and 3) semi-structured correspondence with a range of key researchers, plant breeders, and scholars working with wheat breeding in the northern European context. Although economic and agronomic conditions obviously differ among European countries, I nevertheless piece together insights from stakeholders working in Germany, France, the Netherlands, and Denmark. The study concludes with a discussion of the interaction between institutions, technological regimes, and individuals, and provides an illustrative case study.

Conceptual Framework

Researchers have recently begun to turn their attention to the question of *why* agricultural science and technology are targeted exclusively to intensive monoculture systems, when viable alternative paradigms are known. Concepts of *technological trajectories, path-dependence* (historical factors), and *lock-in* (system feedbacks), borrowed from evolutionary economists, have provided the theoretical foundation. Dosi (1982) for instance asked, "How does a paradigm emerge in the first place and how was does it become 'preferred' to other possible ones?" Dosi defined *technology* as more than equipment and devices, but as inclusive of both practical and theoretical knowledge, methods, procedures and norms. His hypothesis was that economic forces together with institutional and social factors operate as a 'selective device' by influencing criteria such as feasibility and profitability at each level, from research to development. More recently, Possas (1994) has argued that close linkages between R&D and producers creates a cognitive structure which leads to both formal and informal consensus. Another relevant frame for viewing technological change in agriculture is *constructivism*, which assumes the primacy of institutions in shaping trajectories and exposes the role of "unequal power relationships in constructing what is considered truth" (Cleveland, 2000). This is closely related to the concept of the *social construction of technology* (Bijker, 1987) which asserts that, rather than assuming a technology is dominant because it is superior (or more efficient or productive) than its competitors, one must consider which groups of stakeholders define such superiority, and which social, cultural, and institutional elements confer its status. Both of these arose as a reply to the *objectivist* branch of philosophy, which argues that there is an objective, verifiable realm of facts that exists independent of the human mind. In studying phenomena in plant breeding theory and practice, Cleveland (2001) argues for a holistic view, one that accepts that the concept of sustainability, for example, is *both* objective and constructed. This approach "makes explicit the theoretical possibility that knowledge is the result both of social construction influenced by objective social reality and unique individual experiences and epistemologies, while at the same time a result of objective verification of perceptions of the external biophysical world, made possible because of the regularities of that objective world and of human cognition."

In a unique study, Vanloqueren and Baret (2009) recently used the concepts of technological paradigms and trajectories as a basis to explore the development of genetic engineering versus "agroecological engineering." This is an important definition, as it sets agroecology on par with other more dominant modes of engineering agroecosystems. Vanloqueren and Baret found that the direction of innovation was shaped by the nature of agricultural research systems, namely, research orientations and science policies that were explicitly oriented toward economic growth; agroecology, in contrast, has not been linked to these goals, but to broader socioeconomic initiatives. The commercialization of public breeding objectives and the increasing displacement of private for public research were other factors. Overall the authors found that genetic engineering *fit* best into the existing paradigm of high-input, monoculture farming systems, while agroecology presented a fundamental challenge to this paradigm. Hogg (2000) similarly applies Kaufmann's (1988) metaphor of *fitness landscapes* to agricultural systems, writing that "[Radically] different technology would ‘deform the fitness landscape to which other technologies are coupled”, pointing out as well that the fitness landscape is shaped by agricultural policy and property rights; “institutions shape ‘peaks’”.

Joly and Lemarié (2002) have also compared two technological trajectories in plant protection: technology-intensive chemical pesticide regimes, and the more knowledge-intensive program of Integrated Pest Management (IPM). While the authors acknowledged that the pesticide industry largely controls knowledge production and technological development in agribusiness, they concluded that more specific features of the chemical paradigm led to its continued dominance: 1) appropriability of the technology, and 2) technology users’ cognitive frameworks.

Results of Exploratory Interviews with Conventional Wheat Breeders in Denmark and Sweden, 2011

The main objective of the survey was to gauge breeders’ perception of the relevance of agroecological science and sustainability goals to their work. My questions explored the following themes:

- Primary breeding objectives
- Technical, scientific, and economic challenges
- The relationship as a breeder to other stakeholders in the production chain including farmers, processors, input manufacturers, and institutions
- What is the relevance of gene x environment interactions
- The perceived value and feasibility of alternative technological approaches such as increasing crop genetic diversity, breeding for lower-input systems, and application of agroecological technologies.

Due to the proprietary and contentious nature of some of these questions, personal contact and rapport were important elements of the process. Subjects were located by contacting breeding companies within traveling distance of Copenhagen and requesting to speak to scientists with experience with wheat; at each company, this amounted to 1 to 3 persons. Thus the sample is necessarily small. Semi-structured interviews were conducted in-person with a total of seven wheat breeders at three privately-funded companies that lead the wheat seed market in Scandinavia:

Lantmännen SWSeed is the largest of the three firms, with 110 employees at their main office in Svalöv, Sweden. They have breeding stations in Sweden, Germany and the Netherlands, and they focus on the cereals, oilseeds and forages markets in northern and central Europe. SWSeed has 69% of the market share of winter wheat in Norway, 27% in Sweden, and 23% in Finland (Gullord, 2011).

Danish firm **Sejet Planteforædling** focuses largely on the European market for spring barley, but also represents 71% of the market for winter wheat in Denmark, and 3% of Sweden (Gullord, 2011). It has 30 employees. Sejet is 75% owned by the DLG Group, a cooperative of 28 000 Danish farmers and one of the largest agricultural companies in Europe.

Nordic Seed is the smallest firm, with less than 20 employees. It was formed in 2008 from the merger of two Danish seed companies and the DLA Group, a cooperative of 20 000 farmers and agricultural supply companies in the Nordic region. It holds 15% of the winter wheat market in Denmark (Gullord, 2011).

Summarized below are the main themes that emerged from the interviews.

Breeding Objectives

Subjects' objectives with their research program were straightforward, and their primary goal wasn't research-oriented but commercial.

Comments:

- "We want to make superior cultivars, so the company can make money."
- "Feed Europe."
- "Provide the best cultivars for farmers."

- "Keep the company competitive"
- "Earn my salary by designing the top performing cultivars"

Breeding Challenges

- Technical challenges, such as in Denmark how to continue to increase yield with lower inputs (due to regulations)
- Different disease foci in different bioregions (e.g. mildew in Denmark and Norway; rust in France and Germany
- Different technical requirements in different industries (e.g. feed quality in Denmark, bakers and millers in France and Germany)

Main current constraints in breeding, and shifts that have occurred in the industry

Breeders noted that the nature of their work has changed due to the consolidation and increasing commercial focus in the seed industry. Respondents over the age of 40 (n=5) typically had educations in agronomy and plant pathology, and part of their careers had been spent doing traditional field trials. Younger-generation breeders (n=2) had been trained in the milieu of molecular biology, and had spent more time in the lab and none in the field. Due to increasing competition from the bigger firms, breeders reported limited/declining access to agribusiness markets, a more intense commercial focus, and the need to prioritize more generalized markets in fewer crops.

There is very little funding available now for pre-breeding (Pre-breeding is the work that identifies desirable characteristics from more diverse populations and unadapted materials such as wild relatives.) Likewise there has been a severe loss of financial capacity to experiment with material or ideas outside the norm.

- "The breeding companies have changed a lot during [the last two decades]. So when I started we had two companies and we had I think 700 or 800 people working in Sweden in plant breeding. And today we are 150, maybe 200 globally."

- “I was brought up at a time when the control was less intense. Maybe it’s easier for the younger generation, they come directly into a commercial company. I started in a combined research and commercial company.”
- “The aim of course of that money is the same as it was before but we’ve lost the connection between it, between the commercial and the scientific bit.”
- “We have fewer specialists now. We can’t afford experts. There were breeding programs for barley and wheat, oats, oilseeds, and peas, and specific breeders for that purpose and all of them are now gone. That work is now integrated into the conventional breeding programs.”
- “There are less people working on [disease resistance] and we cannot afford to do very many specific projects.”
- “[We don’t have funding to pursue] all the ideas which are not mainstream or variety production. I think that’s needed.”
- “It takes time, that’s the thing. And then we lose our money…. But the bigger firms can still do pre-breeding work, where they probably look at a lot of these things. They also did at Svalov, but isn’t that more or less closed down now? But they’re used to making money on it, so they lost competitiveness on the traditional variety development, so that doesn’t work and then you die anyhow.“
- “The connection to the market is also interesting and stimulating, we should not deny that. In the end that’s what we want, we want our varieties to be on the market and to be of importance on the market. And we want our company to make money so that we can provide new material. But I think it would be a good idea if there were more industry’ students that were in between [commercial and academic].”

Breeding for Sustainability (Variety Traits Suitable for Lower-Input Systems)

Although there was some theoretical interest and awareness of sustainable plant traits, breeders remarked that there was neither time nor funds to pursue them, or that there was limited use or applicability of the information.

Nutrient Use Efficiency

- "I think our modern varieties *are* the most efficient. Yield is simply the best measure of nitrogen use efficiency."
- "It's interesting to see that there are definitely lines that are more nitrogen efficient than others, and what a shame not to use it. If we can put 140 kg of N on 100 000 ha instead of putting 160, it's such a gain. … In the end it has to be driven by economy, so if the N is more expensive, then you look into varieties that are more efficient."
- "That's where it is a point in being a part of a company that sells all the inputs to the farmer and also is owned by the farmers because you get more of the whole view on things. You have a point in arguing that this is more efficient than this. [But if the same company is selling you the N?] well but then the farmer that owns the company wants the money to end up with him, instead of with the company. But sometimes there is a conflict, definitely."
- "As a breeder I'm not really in a position to worry about [who profits, the farmer or the company]. But putting the goals there makes us think about it. In Sweden, our largest client is Absolut Vodka, and they have very specific requirements for farmers for how you grow that wheat. You use these varieties. You use this much nitrogen, no more. So if they say that you can put 1.6 doses [of fungicide], then that's what you can put. Otherwise you get a price penalty."

Weed competitive capacity

- "Not something we look at directly"
- "Interesting but not used in selection"
- "Herbicides are used in trials", "we don't do untreated trials"
- "It is likely that competitiveness would improve if herbicides in trials were reduced, but it's hard to design trials to measure such conditions"

The value of landraces

- "You can't just go and use an old one, it's not that easy"
- "I don't know what their value is, I've never tested any of them."

- "If you go to a landrace now it will probably be susceptible to everything… but there are examples where you find through testing, resistance that was there originally which has been lost in the newly-bred variety."
- "We do need to be a little bit humble. We need to accept that there are a lot of things coming in from different angles where we should not just say we know what's best. There may be things that increase the yield, but it's hard, you can't just make one cross and say there's something here that's good. You have to work with it over 15 years and then maybe some new combo of genes comes out that works well."
- "I know as far as taste there *are* differences [between landraces and modern cultivars]. So, I believe in their value. For root growth there are differences. For root growth I'm SURE there are differences."

Evolutionary breeding, multilines, open-pollinated varieties

- "The problem is the organic people want the stability excluded also, and we're against that."
- "We DO need more diversity, but "[an evolutionary breeder] wants to take a population variety and sow it now, then in 2-3 y it has developed into a better variety, because mother nature has selected. And it's not right. It's fake. You need at least 9999 years to change the medium of genetic variance. The only thing he can change is that some lines will do a bit better than others. But it's right, let's say you have a very sandy soil, it does give you stability (diversity), but it's not genetic diversity over time, it's genetic diversity in the population and in the ecosystem."
- "Multilines, well, we just can't profit from them"
- "Multilines are allowed here yes – in Europe we're based on the platform that you keep diseases lower if you use them. But again it's the production, they don't like it in production."
- "There's no just no money in organic seed. And that's partly *not* because the market is smaller but also because the unfortunately has less of a tendency to buy seed. There is a much higher farm-saved seed in the organic sector than in conv. So they're killing themselves. So it's not going to be solved, and the sad

thing is they put a lot of work and money I think into this new system of having old varieties listed and you can multiply them, but they're not going to be particularly good for organic farming… because they need yield as well as anybody else needs yield. Their cows need to eat as well as anybody else's."

Diversity in the wheat gene pool

- "[the wheat gene pool] might be getting more narrow, but not yet. You have in Europe a lot of gene pools, eastern Europe, France, Norway, Denmark they are not alike at all, very different."
- "No I don't think we are there yet with loss of diversity in wheat"
- "No because they are still locally adapted"
- "We're not trying to have less diversity. It's because you concentrate a lot of the buffer genes inside the good material, and still you can have diversity on other things. But if you have transgenes in, or very big traits, then I think they mask a lot, then I think you have more uniformity."

Breeding for durable (horizontal) resistance

- "You can't test it easily"
- "It would take too much time"
- "It would be more difficult, but it's possible… but then when you put it on the market farmer's might see a little disease and not know what to do, and then we would get blamed."
- "We would actually be happy to have not 100% resistance. We are not too happy to have very specific genes. But in practice it's more difficult to achieve."
- "Well, when you have say one variety which covers most of Denmark, then after 2, 3, 4, 5 years, then you have that race which can attack that. It works, always. Nature will never be defeated…."
- "Resistance always breaks down. That's known, that's biology, we cannot discuss that."

Client-focused research priorities

The relationship between the breeder and the farmer is one of a service provider (breeder) and a client (farmer). Breeders acknowledged that they may be breeding plants for tolerance to increasingly high-chemical input systems, but stated that their hands are tied: to stay in business they have to produce what the market asks for.

Farmer agronomic requirements

- With our trials "we have to try to mimic what the farmers do"
- "We have a close connection with farmers, we're very aware of how they grow things and what they do. There are a lot of farmers visiting here."
- "[With bread wheat, the millers] have specifications, we have quite frequent meetings with them, especially of course with millers that also belong to our coop, because the largest mills here also belong to the same company that we belong to. And they're always very interested when new varieties come, we have something called industry tests, and we have to have fairly big amounts of a variety… 30 tons or 60 tons before they can test it in practice in the mill. I don't think it would be possible to market a spring wheat variety which the millers have not accepted before hand.
- It's probably a little bit easier for us [to serve the smaller markets], because we are owned by the farmers cooperative. They dictate what to do in a way. We want to keep it. We still have programs on grasses, clover, we have rationalized a lot, we have only half the crops that we did 20 years ago, but we still have *more* different crops than most companies and that's to a large extent due to our owners.
- "There's a huge range [of farm sizes in the cooperative]. But the biggest ones they raise their voices higher, also in the farmers union."

Low tillage, decreasing rotations, and intense disease pressure

- "Here in Sweden there is more rationalization than in Norway, where farmers still have time to plough their fields… and that brings some issues with pests and diseases and with residuals of straw in the fields."
- "The farmers have gone more to wheat after wheat"

- “We know on the macro level, you can influence the environment by your cropping – not only on a variety level, but on rotation and cropping intensity.”
- “We have lost resistances very quickly because some (larger) farmers are reducing rotations, but we can't tell them what to do.”
- “Yes, for really sustainable growth you need to have a little bit of equilibrium – and it’s not what we are doing in modern cropping.”

1.5 Plant Breeder Protections, and EU Regulations

Plant Variety Protections (PVP)

- “If we didn’t have PVP protection, then we wouldn’t have breeding”
- “[Without protection] you can’t get it listed, you can’t sell it, and you can’t make money.”
- “We use the DUS system like the rest of Europe. It’s been that way for a long time, we like it, it doesn’t pose any problems for our program.”
- “But some old varieties are a bit difficult to kill off, the farmers like them and they hold on to them. There is a 28-yr old variety, one we don’t want them to grow anymore because we don’t earn any breeders rights/royalties anymore. [Our firm] doesn’t want to have more varieties in spring wheat, so a new one must replace an old one. It’s an economic decision. Higher costs.”

Patents

- “We do *not* need patent protection, we need innovation protection”
- “[Loss of breeders’ exemption means] we can no longer cross and use someone else’s variety, and keep diversity.”

Molecular Technology

- I guess when we started working in markers we expected it to take off much faster and be much more useful than it is today. It has not been a success til now, it has been a lot of waste of money. It's not yet good enough, there's not yet enough good markers."

- [As a molecular biologist] I don't think these new SNP's will do much in the future."
- "What we need is a faster and better way of getting new genes, of finding new genes and of marking them with a diagnostic marker. But you always come back to that problem that you need the phenotype."
- "We also made some GM trials, but the political scenario did not allow us to grow it. This money has also been wasted."
- "Markers for a few specific traits, and the kind of traits that would work in all environments (resistance, height), these are what we keep looking for."
- "The technology's not so developed yet that it would be useful for us… right now we use a lot of work to figure out *what* the parents have, *which* genes and markers and *what* to test. We do not have the most optimal tools because they are too expensive."
- Also there is a problem for Scandinavian but maybe also for European companies to *find* plant breeders, because the students that take the classes now they don't' want to be come field type plant breeders. I wouldn't say they don't want to but they don't know of it. Because of course education is directed into gene technology, microbiology."
- "Our newest colleague… she's a molecular breeder, she works with pre-breeding in oilseeds. But she's learning, she's adapting. [She will need to] work for a couple of years in a company and also work with the field part. Because it's so easy otherwise to think that things are going to be solved so quickly and easily by putting a gene here or there or by selecting, 'we can select everything with markers', but then we need to put them in the field."
- "There's a cultural gap between the two disciplines [molecular biology and plant breeding]."

Discussion of Survey Results

Survey questions that asked breeders about the relevance of agroecological methods (rotations, plant spacing, intercropping, organic fertilizers) to their research work were difficult for them to answer. Likewise, questions about the systemic consequences of selecting in favorable environments often resulted in a shrugging of shoulders, or "I'm not sure what you're getting at." One representative response was: "It's not something we look into much. I would say we look upon [the crop environment] as fixed." In large developing economies in Latin America, Asia and Africa, one observer has stated that most agricultural researchers, academic faculty, and extension workers are simply unaware of the existence of agroecology as a viable farming model, or of the legacy it has enjoyed in other countries (Paschoal, 1991). Vanloqueren and Baret (2009), in their study comparing genetic and agroecological research trajectories, report a similar reception from scientists:

> Many scientists do not explore these agroecological innovations because "it goes against the flow", as a scientist explicitly stated during an interview, when asked why cultivar mixtures were not being researched to create systems resistant to fungal diseases. Scientists and stakeholders refer to current social and economic barriers impeding the use of some possible innovations by farmers today to justify the research deficit. Current barriers are seen as permanent immovable obstacles. As a result, some agroecological innovations are considered to be 'theoretically valid' but 'not feasible' in modern agricultural systems, as they 'go against the flow'.

These results suggest that the orientation of breeders' research activities is—or is perceived to be—largely constrained by other elements in the agribusiness system, namely, farmers and agribusiness clients, and the commercial and regulatory environment—both of which value cultivars based primarily on yield performance in a high-input agroecosystem. Or, more simply put, "The plant breeder's aim is to produce and identify genotypes that will succeed in the 'crop' environment" (Sedgley, 1991). And in conventional agriculture, that means high-input monoculture. The following comments stand out for their poignancy:

- "It's not that easy [to ask whether some parts of the system are unsustainable, like chemical inputs]. It's really difficult to understand how the pieces… the example with the roundup ready and the weeds, that will be an example where we know where it's going. But who shall decide if the yield increase [isn't worth it?]… let's say you only need to have one chemical at home in the barn, that is also a benefit for a country or for a farmer, and it must be looked at as a trade off as to what happens with the weedy crops. So, who can decide that?"
- "Normally we [as breeders] would not look upon [whether something is sustainable], because we know! We know, so we will not try to find… it must be business people… It will not be biological people, it must be some people who are looking from other perspectives in the society. We are not the ones which should judge that. Copenhagen business school, they must have some. [What you're asking], it's quite another story, it's not a biological story, or is it?"
- "We have a bigger pressure on us to produce figures on how many lines go into trials, how many lines are on the national list, how many lines are registered, there is a higher focus on that today I think. The company, the management, are trying to find ways of controlling our work and to quantify how effective we are, how efficient is the breeding program in terms of delivering varieties. They're trying to find parameters to measure the research process. We try to help them but it's hard to find those parameters."
- [We need new varieties because the resistances break down, it may be 3, 5, 8 years. Or really it's outyielded by the new ones. It could be resistance, it could be quality, but usually the yield is the top.
- "We can't earn money on [multilines or mixtures], so we don't do it."
- "Personally, *I* can't influence the farmers practice rotation-wise, I can't influence them after they have bought a big piece of machinery for no-till. Then that needs to be used, there is nothing else to do about it. I don't raise my voice and say 'varieties are not the thing that influence this [disease] the most.'"
- "One thing with rotations that is very much spoken about now is *fusarium* which is an increasing problem, which is due to bad rotations, and bad cultivation of the soil and things like that. So that has increased the pressure on

> us to have specific *fusarium* trials to try and get rid of the lines that are the worst at least."

While it is not valid to generalize from these interviews as to the motives of other conventional cereal breeders (Yin, 1994), these exploratory findings are instructive and were instrumental in directing me to the main focus of this thesis. On reflection, implicit in my approach was the idea of the individual breeder as an autonomous agent, whose conscious choices can be attributed to technological or cognitive factors. Instead it became apparent that, while each breeder is an independent scientist with a unique background, research interests and motivations, he or she pursues their work within a technological trajectory shaped more by systemic structures (agribusiness markets and institutions) than by individual choices. "Complex institutions have well-established pathways of theory and practice, often bolstered by factors beyond the individual breeder" (Mcguire, 2005). Thus not only are breeders working within well-articulated scientific paradigms that reinforce high-input use, they are constrained by economic, social and institutional frameworks. Vanloqueren and Baret (2008), in a study that asked why lower-input, disease-resistant wheat cultivars in Belgium have been slow to develop commercially despite their utility, counted the breeder and breeding company objectives as only one among 12 factors that impeded their use. Other prominent factors were lack of farmer adoption, the deeply-rooted influence of input-supply companies, and the governing principle of gross yield in both extension research and agricultural policy support.

I present next the results of research exploring the development of A) plant selection paradigms and technologies B) institutions that comprise the modern seed system in the European Union, and analyze their effect on the breeding of plants for fitness within lower-input systems.

A Brief History of Plant Selection Paradigms and Technologies

Cultivated plants are in a sense *technologies*, and are inextricably linked to the larger human technological project of agriculture. In this section I use the evolution of cultivated wheat*, triticum aestivum*, as the thread by which to trace such a technology from its early domestication to modern high-yielding forms. Specifically I look at its genetic and phenotypic development, in the context of human selection paradigms, its effects on the wheat genome, and its association with changes in the crop environment or agroecosystem. The purpose of this chapter is to briefly chronicle the influential scientific concepts, socioeconomic processes, and farming systems that together guided the technological trajectory in plant breeding during through pre-industrial times and into the 21st century. As social science scholarship in the history of plant breeding is sparse, and in many ways the trajectories of plant breeding science follow a similar course in many Western European countries, I attempt only to give a broad outline and have intermingled histories from several European and Scandinavian countries. Changes to the wheat plant and its agroecosystem will lastly be discussed in terms of sustainability.

As an object of analysis I focus on the breeding of spring and winter wheat (bread wheat) in the northern European context, for two reasons. As the main component of most arable crop rotations in this region, winter wheat is the largest cereal crop grown in Europe and the most economically important food crop in both conventional and organic production systems (FAO, 2008; Konvalina et al., 2009). As conventional wheat production consumes 30% of total pesticide use in the EU, even incremental progress toward reduced input use in wheat production would have wide-reaching environmental implications. Wheat is also predominantly grown as an input to the human food chain, with its high demands for uniformity throughout production and processing; thus a focus here highlights issues of crop diversification that may be less problematic in other crop species, for example vegetables, or cereals and legumes bred for animal fodder.

Fig. 1. Diversity in spike morphological structure of wheat landrace accessions at Gene Bank at RICP Prague. Analysis for components of yield and contribution to harvest index can include grain weight per spike (g), 1000-grain weight (g), grain number per spike, node number per spike rachis, spikelet number per spike, grain number per spikelet, grain number per rachis node, spike rachis length (mm), and plant height (m). Source: Martinek and Bednár (1998).

EARLY FARMER SELECTION IN WHEAT AND ITS EFFECTS ON GENOTYPE, PHENOTYPE

In the roughly 10,000 years since its domestication, wheat has been continuously transformed by the selection pressures imposed by the environment of human agricultural systems; in the process it has undergone several important changes to its genome, its morphology and its relationship to the crop community. Like other self-pollinated crops (e.g. rice and many grain legumes), wheat generally breeds true to type; outcrossing is rare, and thus natural selection on the genotype acts very slowly. Artificial (human) selection of desired plant traits was an important technological innovation and, especially in wheat, was pivotal in the shift from hunter-gather societies to sedentary agricultural societies and ultimately civilization itself (Purugganan & Fuller, 2009).

The shift to agriculture from foraging meant a shift in human labor investment in fewer plant resources, and therefore a reduction in genetic diversity over wild crop relatives (Purugganan and Fuller, 2009). Yet early in the domestication process, the wheat genome itself tripled as it transitioned from wild Einkorn (the diploid *Triticum monococcum* ssp *aegilopoides*) and wild Emmer (*tetraploid Triticum turgidum* ssp *dicoccoides*) to its recognized cultivated forms of durum wheat (*T. monococcum* ssp *monococcum*) and bread wheat (*T. turgidum* ssp *dicoccum*). As it traveled with humans beyond its center of origin and was adapted to different climate conditions, continued natural and artificial selection increased its phenotypic diversity over wild populations; today wheat is blessed with one of the largest and most complex genomes of all crop species (Ribaut et al., 2001) and in 2009 was grown on 225 437 694 ha worldwide (FAOSTAT 2010).

Changes to wheat's genetic make-up were accompanied by changes in morphology. The earliest and most profound changes (the 'domestication syndrome') served the technological function of facilitating harvesting and germination (Fuller, 2007). The main traits associated with this evolution include:

Increased seed size: this not only represented an increase in the proportion of harvestable material, but it gave plants an agroecological advantage in selecting for seeds that would produce vigorous seedlings and thrive in human-disturbed, tilled soils (Baskin and Baskin, 2001, as cited in Purugganan and Fuller, 2009).

Free-threshing: The seed coat of free-threshing forms is no longer tightly attached to the seed, so plants can be easily threshed (loosening the husk by beating or flailing them against a hard surface) and winnowed (tossing the grain into the air so that the lighter husk drifts away leaving only the naked grain).

Non-shattering: the loss of the abscission layer at base of the spikelet prevents natural seed dispersal (seed shattering), making the grain easier to harvest and sow.

Tendency toward annualism: reduced tillering capacity and perennialism, as crop density increases, and seeds from desired phenotypes are saved from year to year and replanted.

Compact panicle: selection for a denser seed head (spike) has been noted in a number of cereals (Zohary and Hopf, 2000)(**Figure 1**).

The development of these and other traits that served human systems came at a cost to the plants' competitiveness in wild ecosystems. The input of human labor in seed transplantation and weeding, for example, enabled the plant to allocate more resources to grain production than competing against neighboring plants and weeds. The agricultural production systems that shaped these early wheats were thus characterized by a trade off: high inputs of human labor and sophisticated agroecological knowledge (Conway, 1987) in exchange for increased starch and protein; in other words, inputs were labor- and knowledge-intensive, versus energy intensive. Associated technologies included hand sowing and weeding, sickles, harrows, simple irrigation and use of rainwater. Agronomic performance was measured in terms of stable production of enough grain for subsistence throughout the year and enough viable seed for next season's planting. Selection for grain quality was made on the basis of cooking, processing, storage, and aesthetic preferences. The size and shape of wheat grains is a prominent feature of domestication and been selected for and manipulated even in very early agrarian societies (Gegas et al., 2010)(**Figure 2**). Selection and seed saving were performed by individual farmers and households.

Fig 2. Variation in Grain shape and size in Ancestral subspecies of the genus Triticum (Gegas et al.)

As throughout much of human agricultural history, the prevailing approach to plant selection until around 1900 was what is now termed *population breeding* or *mass selection*. This method shapes an overall population by first selecting individual plants according to their phenotype and performance, then bulking and growing out their seed as a mixture. This is a slow but effective method of improvement in self-fertilizing crops like wheat, and has historically produced the heterogeneous and heterozygous populations known as *landraces*—varieties with high capacity to tolerate biotic and abiotic stress, high yield stability, and intermediate yields under low input agricultural regimes (Zeven, 1998). Mass selection is most effective on highly heritable traits, and mitigates the large influence that the environment has on the development, phenotype and performance of single plants. Wheat communities in traditional agricultural systems were generally characterized by a diversity of species over time (for example rotations, shifting cultivation) and space (genetically heterogeneous crop populations interacting with weeds and wild relatives). In medieval England, for example, landraces of red and white wheats, rye (*Secale cereale*), oat (*Avena sativa*) and barley (*Hordeum vulgare*) were grown and milled for bread as mixtures; there was also diverse morphology within wheat populations (e.g. seed head density varied from lax to very dense)(Letts, 2000). In genetically diverse mixtures, each plant will exhibit a slight variation in environmental response, reflected in differential height, leaf habit, competitive ability, nutrient use efficiency, disease resistance, and phenology (flowering date, maturity); thus while the grain yield of an individual genotype will vary over time, the crop community as a whole has a plasticity in performance that provides yield stability over time, despite variations in rainfall, temperature or nutrient availability across sites. Archaeologists have recently speculated that it was not annual grain yield *per se* that drove early evolution in wheat populations, but rather yield stability (Abbo et al., 2010). Although grain yields have increased slowly over millennia of farmer selection, the high yield stability that characterizes landraces often comes at the expense of gross yield (Harlan 1992, Zeven 1998).

Though some early selection by farmers has been termed “unconscious” (meaning incidental to the act of farming), both pre-industrial and contemporary subsistence farmers are known to observe and “experiment” with new germplasm (Richards 1989, Brush et al. 1981, Van der Ploeg 1993). Heterogeneous fields are not only maintained as a hedge against fluctuations in climate and disease pressure, but also represent the raw material for ongoing farmer experimentation and the generation of new genotypes (Van der Ploeg 1993). Crop heterogeneity promotes hybridization and crossing between ploidy levels (Brush et al. 1981), and has been crucial in shaping crop genomes. Thus early crop communities have been shaped by environmental variation, genetically heterogeneous communities, and farmer selection practices.

INDUSTRIAL REVOLUTION

The Industrial Revolution of the 18th and 19th centuries had a profound effect on agricultural systems in England, Europe and throughout the world. At the dawn of the revolution agricultural practice in Europe meant smaller, mixed cereal, legume and vegetable farms for subsistence and increasingly commerce; broadcast sowing on unfertilized fields; and hand harvesting with simple tools. The addition of machine power and fossil energy to agricultural work transformed production levels per unit of land and labor (McIntyre et al., 2009). Production was still labor intensive, but a steady progression of seed drills (in 1701), iron ploughs (1730), mechanical threshers (1784), and reapers and were developed, increasingly displacing farm labor to the cities (Overton, 1996).

With mechanization came intensification. During this period in Europe, fallows following cereal production began to be replaced by legumes, potatoes and sugar beets, and the traditional 2 to 3 crop rotation soon waned under pressure of continuous cultivation (Van Zanden, 1991). As soil fertility concomitantly declined chemical fertilizers were increasingly sought, in the form of guano, nitrates from South America, night waste from cities, and bone ash as a phosphate source. In food processing, millstones were replaced with steel rollers and steam power was added; the bran and seed coat could be precisely removed before milling, enabling longer storage and transport and infamous “white bread”. Mechanical mixers and kneading machines also appeared, together with mass production in continuous ovens and the addition of preservatives and extenders to enable industrial processing and improve shelf-life.

In the context of rapid change in agriculture, industry, and society, agricultural science emerged as its own field in the mid 1800s, with philosophical roots in Descartes' and the fields of biology and chemistry (Maat, 2011). The agrochemical industry was subsequently born as an offshoot of the chemical industry in the late 19th century (Joly and Lemarié, 2002). The genealogy of thought underlying agricultural research, including plant breeding, begins with French philosopher Descartes' mechanical conception of the functioning of nature[2]; this is built upon later by Newton who prioritized linear, quantifiable, physical phenomena, superimposing mathematics as a model for studying the "messiness" of biological systems. The Cartesian-Newtonian world-view also shaped economic theory, with the resulting rationale shaping "a vision of progress based on unlimited production growth in agriculture echoing the concept of endless growth in mainstream economics" (Marechal et al., 2008). Agriculture became an object of optimization. Statistical significance testing became important for organizing experiments, in order to reduce the variability inherent in natural systems (Maat, 2011). The earliest "plant breeders" of this era were botanists immersed in this scientific milieu, and were intrigued by interspecific hybridization and the mechanisms of diversity (Bonneuil, 2009). The birth of scientific plant breeding toward the end of the 19th century heralded a paradigm shift that, together with technological changes in farming systems, would lead to tremendous advances in crop yields.

Coinciding with the rise of scientific crop improvement and robust international trade networks, the late 19th century also saw a commercial seed trade begin to take shape in Europe and the United States. Unfortunately farmers had little means to verify the varietal identity of a given bag of seeds, or to know the likelihood of whether it would germinate; they were vulnerable to outright fraud, inaccurate labeling, poor quality seed, and the risk of seed-borne diseases, all of which increased the uncertainty of an occupation already fraught with risk. Breeders as well had no protection for their innovations. It was in this context that the first seed testing stations appeared in

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[2] Marechal (2008) suggests that farmers of this time resisted scientific innovations in agriculture as "they did not accept the vision of [the animal] purely as a "machine"". And Bourdon (2003, as cited in Marechal) notes that scientists have often preceded farmers in conceiving and applying new farming practice.

Germany in 1869, and later across Europe, to assess the production potential of seed before it is planted (Muschick, 2009). By 1905 Germany had begun to regulate seed sales by establishing an official variety register that listed variety names, traits, and results of performance tests (Tripp and Louwaars, 1997), and other countries soon followed (McGuire).

THE DAWN OF GENETIC SCIENCE

With the arrival of the 20th century came a sea change in the understanding of plant traits, due to the re-discovery in 1900 of Mendel's laws of inheritance and the birth of genetics. Where 19th century biologists viewed inheritance as a "blending" of phenotypic traits, genetics ushered in a new paradigm of separable "units" of heredity. Conceptually this unit, the gene (and its components, alleles) enabled humans to understand the phenotype decontextualised and separable from its origin and the complexity of its environment.

Danish botanist WL Johannsen first put forward the concepts of *genes* and *alleles*, and the conceptual distinction between genotype—a plant's genetic make-up—and phenotype—its expression (Bonneuil, 2008). Johannsen showed that by self-pollinating a single plant and its progeny for about six generations, genetic uniformity is achieved and there is no further variation in the progeny. Thus the pure line was born, a homozygous, genetically uniform cultivar. Genetics gave breeders the practical basis for solving the "problem" of variation in crop populations, and enabled a shift away from mass selection to recurrent selection, or the selection and manipulation of quantitative, single gene characters (See Figure 3 for an example of a recurrent selection process). "Classical" plant breeding emerged, and the focus on the population was largely abandoned in favor of selection for the "best individual". Genetics greatly accelerated the selection process because now breeders had a tool for understanding the mechanisms of male and female crosses and their outcomes. Specific "defects" could be eliminated or bred out: disease resistance could be bred into a susceptible but high-yielding genotype, for example, or earliness could be added to a variety prone to later water stress. And at the same time, through inbreeding, a desirable trait such as strong straw could be "fixed" in the variety. This was a tremendous boon to selecting for plant improvement, as without continuous artificial selection, valuable agronomic traits that have taken decades to achieve in a cultivar can quickly be lost due to processes of natural selection.

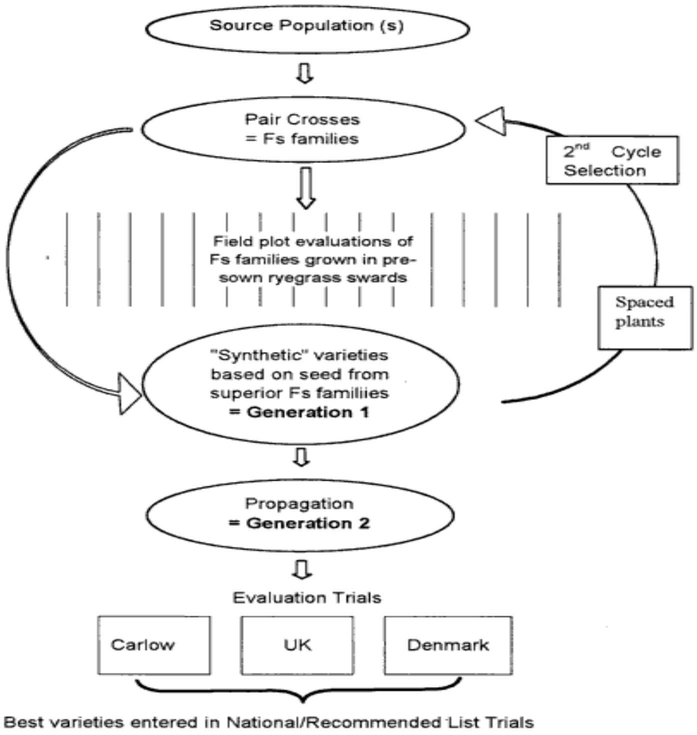

Fig. 3. Illustration of recurrent selection cycle. Conley et al., 2009.

Breeders put genetics to use in the selection of cultivars fit for increasingly intensive and mechanized production. The rise of the genetic paradigm coincided with the first successful manufacture of ammonia on an industrial scale in Germany in 1913. Applied to wheat and other cereals, mineral N had a direct effect on yield, and statistical methods were introduced to evaluate the yield (or N-response) potential of cultivars (Sedgley, 1991).

Scholars have commented that with genetics arose the first seeds of appropriability in the agricultural sciences (Hogg, 2000). Indeed, the first system for the protection of breeders' rights emerged in France around 1920, based on criteria for "distinction, homogeneity and stability"; this is the origin of standards that were later adopted by the EU in 1961 as part of the UPOV treaty (Berlan, undated). Before genetics and the inbred line, precise homogeneity and stability of traits in offspring were simply not possible in plants that weren't clonally propagated. Implemented differently in different academic research cultures across Europe (Maat, 2011), genetics brought about a dramatic reorientation in the biological sciences, away from a Darwinian interest in systems, variation and interactions, to the "almost obsessive quest for purity, serial homogeneity, and fixity" (Bonneuil, 2009) that would come to dominate 20th century plant breeding. Genetics had its origins in the culture of industrial rationalization of the late 1800s (Bonneuil, 2008); it was a "science for the times: it fit the interventionist, manipulationist temper of the early twentieth century, fresh from the conquests of the steam engine, electricity, telegraph and telephone, and most recently, the internal combustion engine" (Marglin, 1996).

Post WWII Europe and the Ascendancy of Science

The period following WWII in Europe was marked by the ascendancy of science in agricultural production: seeds, fertilizer, crop protection and technical knowledge all became off-farm inputs, standardized and produced outside the farm for increased efficiency following the "logic of rationalization" (Bonneuil et al., 2006). Bonneuil et al. (2006) have written in detail about the effect of industrialization on farming practice in France at this time. Most notably a new division of labor arose between the farmer and professional agronomists and other scientists. The farm became an object of optimization and crop development became the exclusive domain of "registered breeders," while the farmer was redefined as an end-user of off-farm inputs and relinquished their function as innovators and conservators. Jean Bustarret, head of the Institut National de la Recherche Agronomique (INRA) Genetics and Breeding unit in 1946, summed up this revision when he asserted that "landraces arose via 'natural selection,'" obscuring the work of 10 000 years of mass selection (Bonneuil et al., 2006)[3]. In industrialized Europe in general, "modern farmers had to accept a greater dependence in their decision-making processes" (Maréchal et al., 2008) and rely increasingly on the advice of extension agents, who were themselves predominantly

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[3] Author's translation. "[Bustarret] considère ces variétés-populations comme 'des écotypes, issus de populations à l'intérieur desquelles a joué, pendant de très nombreuses générations successives cultivées dans le même milieu, la sélection naturelle'. Le choix des mots est révélateur."

mouthpieces of the agrochemical industry (Maat, 2011). Seed selection and production became physically separated. "Experimental space" was moved to the laboratory and experiment stations, and on-farm experiments were often superseded by crop physiological models gleaned from systems ecology and cybernetics; as Maat explains, crops became "a set of linear equations, acting as machines". The farmer's knowledge, rooted in the experience of working the land, was replaced by "the knowledge of plant breeder, chemist, or engineer, rooted in the laboratory or the experimental plot (Marglin, 1996).

The seed itself was honed as an industrial input, an "intensive object of scientific management" that must be standardized to fit the requirements of mechanized processing and increased chemical inputs (Bonneuil et al., 2006). The relocation of innovative labor to the laboratory helped steer the trajectory of plant breeding toward more rationalized lines. Faith in the primacy of genetic tools was reinforced by the discovery of vertical resistance and gene-for-gene relationships in the early 40s (Flor, 1971). This era also saw technical advances in hybridization and synthetic varieties (particularly in maize), mutation breeding, and the use of cytoplasmic male sterility to control inheritance. The "prestige of science," writes Marglin (1996), "made the plant breeder, a tinkerer operating on largely hit or miss lines, into a geneticist…and guided research along scientific lines" as opposed to the former more empirical approach of population improvement. The move coincided with a larger project of centralization, integration, and economies of scale within agribusiness; a process that had important consequences for diversity and seed sovereignty, as breeders increasingly bred for broad adaptability and increasing ease of appropriability. The post-war period in Europe also saw the development of modern pesticides, and the wide availability of low-cost mineral fertilizers.

It is also in the 1940s that formal state seed system structures begin to mature in many countries in Europe. The concepts of *stable* and *uniform* first become defining characteristics of the ideal "modern" variety; these terms provided a sharp conceptual break between the new F1 hybrids and clones and the unpredictable world of open-pollinated varieties (Bonneuil et al., 2006). These standards, known now as DUS -

distinctness, uniformity, stability - were linked to early intellectual property concepts and by definition excluded the more variable and less patent-friendly landraces. Uniformity and homogeneity in plant material truly began to coalesce as guiding principles of seed production and trade. By 1949 in France, only varieties in the official national catalog could legally be marketed, while in Scandinavia, the variety concept at this time was still based on heterogeneous populations composed of mixed lines. A robust economic focus emerged as part of post-WWII nationalist momentum, where modern "science" and the "market" are now responsible for determining value. Agriculture became subsumed by the productivist paradigm, which "shifts the focus of economic policy from utility to consumption, and prioritizes economic growth" (Maréchal et al., 2008). State farm policies thus began to form around the paradigm of chemical inputs, and agricultural price supports and input subsidies were born (Cowan & Gunby, 1996; Cleveland, 2001). The concept of "value for cultivation and use" is also introduced at this time in association with the requirements of intensive agriculture (yellow rust resistance) and the food processing industry (baking strength) (Bonneuil et al., 2006).

THE GREEN REVOLUTION

The Green Revolution was a perfect storm of scientific intervention in crop yield potential: the climax of integration of added inputs, irrigation, and targeted genetic manipulation. In the 1950s at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, wheat breeder Norman Borlaug successfully crossed a semi-dwarf Japanese wheat with a taller, disease-resistant, high-yielding variety; this produced a wheat variety with shorter, stronger stems that: 1) could withstand heavy doses of fertilizer and support larger seed heads, 2) were more amenable to machine harvesting, and 3) meant a greater proportion of assimilate was partitioned into grain, further increasing the ratio of yield to biomass. By 1963 Mexico's wheat harvest was a spectacular six times larger than in 1944. Dwarfing in wheat and other cereals solved an important technical bottleneck in agriculture (Robinson, 2007; Possas) of how to add a yield promoter (nitrogen) without lodging. Yet an agroecological trade-off was made: higher yield was achieved at the expense of the competitive advantage of taller grasses. High-yielding cultivars of the Green Revolution might better be called input-responsive cultivars.

The Harvest Index & Donald's Ideotype Concept

In 1968 Australian agronomist Colin Donald proposed a new orientation in plant design: rather than selecting high yielding lines from the diversity of existing populations, or eliminating defects from known successful cultivars, Donald suggested that breeding should instead proceed toward the realization of an idealized plant type, or "ideotype". As in other mechanized industries, Donald theorized that breeding should be able to engineer such an ideotype based on a composite of morphological traits with known potential to contribute to grain yield. The aim of this "more deliberate analytical approach" was to reduce empirical research needs and thus speed up the selection process (Sedgeley, 1991). What was novel about his approach was that it overturned the assumption that the cultivars with the highest yield potential are the same plants that yield best in a competitive selection environment. Instead, Donald proposed, what may be a weak competitor in a "natural" plant community might be the most successful plant type in industrialized agricultural communities.

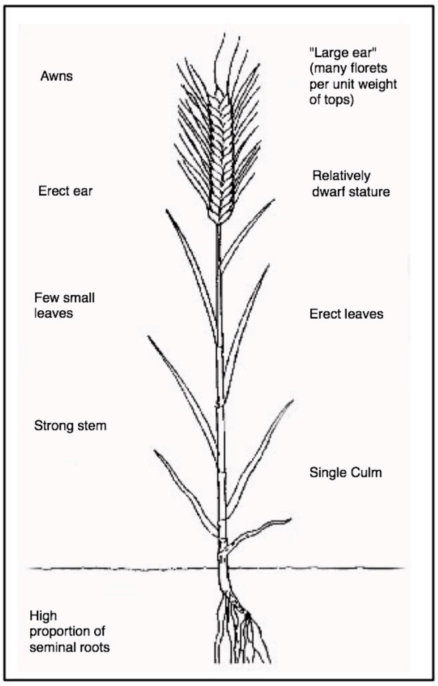

Fig. 4. A hypothetical wheat ideotype with features presumed conducive to high grain yield as a crop community (Atwell et al., 1999)

Based on an understanding of crop physiology and the impact of competition on yield potential, Donald proposed that those physiological features that enable a plant to be more competitive—to more successfully capture resources than its neighbors—are to be selected *against*. In terms of morphology, Donald's model plant was shorter, had a more compact seed head and erect leaf habit. In its growth habit it had less early vigor and a less robust root system; it tillered less and ideally had a single culm, sending more of its assimilates into grain production and less into resource capture (see **Figure**

4). Such a cultivar had little use for competitive ability, as its needs for nutrition and protection were provided by mineral fertilizer and chemical pesticides and herbicides.

Donald devised the ideotype in the service of another emerging concept in agricultural research, that of the Harvest Index. Building on previous concepts such as "economic yield" or "biological yield," the harvest index articulated the modern economic essence of agricultural production. Gross yield had matured as an organizing principle, and breeding would thus proceed to refine selection on the basis of enlarging the portion of economic value. With its roots in the high-input, monoculture paradigms that contributed to such great yield gains during the Green Revolution, this proposed cognitive framework went further, enabling breeders—conceptually at least—to reduce the "noise" and complexity of genotype-environment interactions down to a binary relationship between input and yield. Donald explicitly excluded diseases and pests from his discussions, under the assumption that these protections would be provided by outside inputs; he furthermore defined regional and cultural factors as aspects of the environment that must also be left out of the equation (Sedgley 1991). The ideal crop stand was thus essentially a replication of the laboratory: a sterile environment, devoid of interference from diverse flora, microfauna, or biotic stresses; likewise the ideal variety was responsive to inputs, not the environment.

Though the ideal of the ideotype was difficult to achieve in practice, it was nonetheless influential in shaping breeding program objectives around the world and in other crop species (Sedgley, (Maat). Viewed against the backdrop of thousands of years of human selection, the aim of increasing the harvestable portion of a plant is not necessarily qualitatively different from that of our ancestors. But where previous breeding innovations during the course of pre-industrial agriculture gave rise to great variability in phenotypes linked with diverse cultural uses, modern cultivated varieties are much more of an "economic phenomenon" (Chable, 2003). Donald's model refined for agricultural science the terms of what a crop community is—a heavily fertilized, dense stand of genetically identical individuals—and is important for understanding the tautology that is high-input agriculture.

> Donald's legacy in one sense is breaking down yield into heritable components, such as panicle size, head compactness, seed number and seed size. It forms a 'search image' when selecting rapidly among thousands of phenotypes. (McGuire)

This search image of plant architecture optimized for industrial farming is embedded among conventional breeders and seed system stakeholders today (Philipp Steffan, personal communication Aug 14 2011), and is highly relevant to the design of more sustainable crop systems. But each physiologic change to a plant comes at a metabolic cost, and the gains in harvest index have been "matched by losses in other [useful] characteristics" (Wolfe 2003). Ecologist Carl Jordan (2002) summarized the facts eloquently:

> What plant breeding does is change how the captured [solar] energy is used. When crop plants were domesticated, certain traits, such as ability to compete for nutrients and ability to resist pests, were traded for other qualities, such as high production, especially production of grain. The farmer took over the functions of plant nutrition and pest control using machinery and agrochemicals. What plant breeding does not do is increase the amount of energy captured through photosynthesis. [Making changes to plant architecture does not mean that] scientists have overcome the first law of thermodynamics: Matter and energy cannot be created, only transformed.

In this light, the phrase "plant improvement" is a misnomer, and in an age of climate extremes and competition for resources society must ask what the energy costs are of conventional "improvement", and which stakeholders such improvement serves. The conventional wheat ideotype is useful as an object of analysis of the specific costs of certain physiological features; these features not only have negative consequences for agroecosystems which are externalized and obscured by mainstream agricultural paradigms, but they squander the "free" services that ecosystems provide. These consequences are summarized in **Figure 5.**

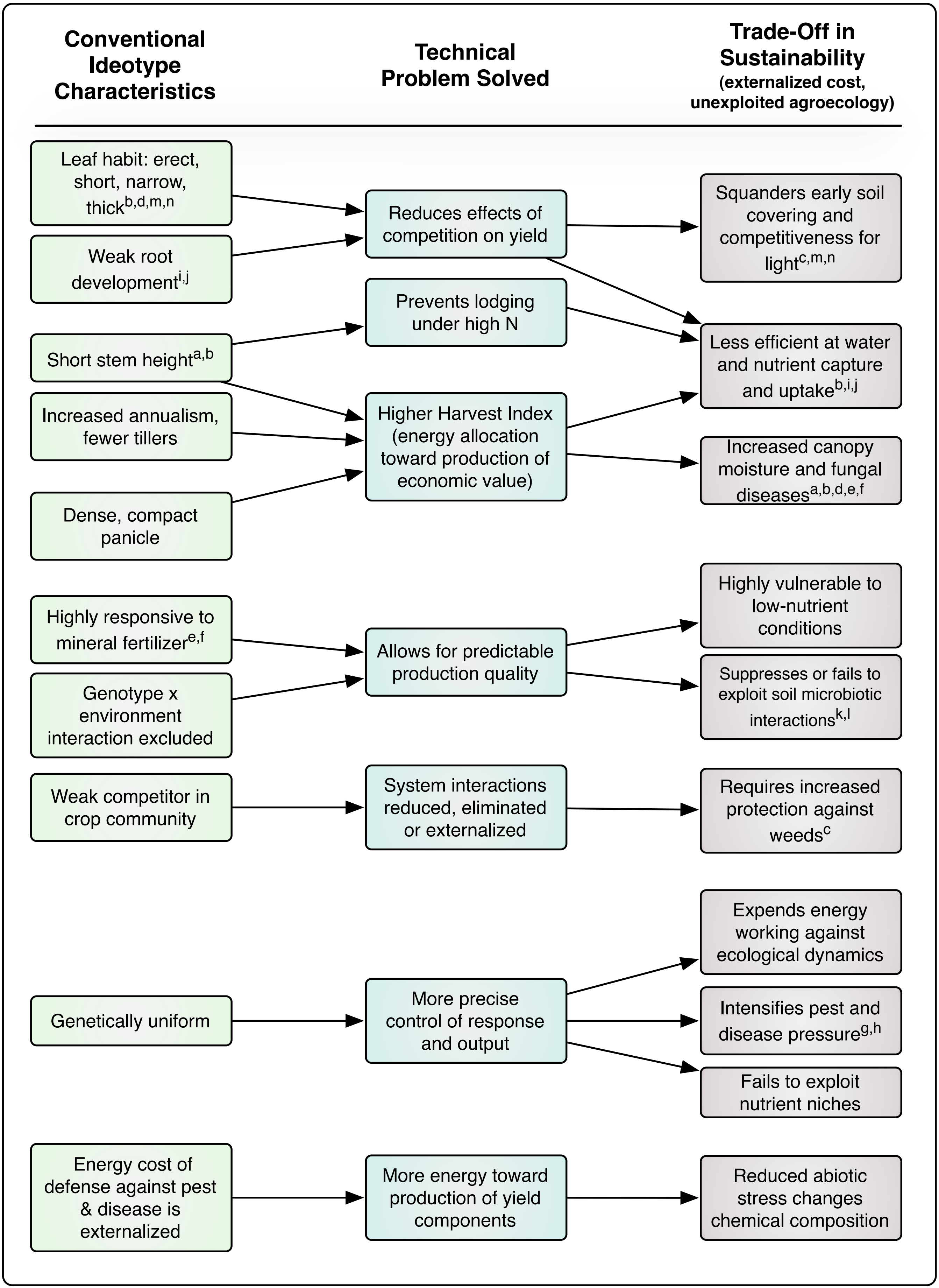

Fig. 5. Cost-benefit analysis of model high-yielding wheat cultivar. Sources: [a]Scott et al. (2007); [b]kunz (1983); [c]Petrasek (2007); [d]Engelke (1992); [e]Heier et al., (2005); [f]Tamis and Van Dan Brink (1999); [g]Milus et al. (2009); [h]Mesterházy (2002); [i]Waines (2007); [j]schweiger (2007); [k]Hetrick et al. (1993); [l]bosco & Picard (2007); [m]Tanner et al. (1966); [n]Hoad et al. (2006)

MOLECULAR BIOLOGY AND BIOTECHNOLOGY

The trajectory of plant breeding science intersected with innovations in molecular biology in the late 1970's, synthesizing knowledge and technology from genetics and biochemistry, and increasingly applying the expertise of plant physiologists and plant biochemists (koorneef). Although the use of biotechnology in breeding departs from many of the methods of conventional selection, in many ways it builds upon orthodox paradigms and aims. Three significant applications of molecular biology to plant breeding have been tissue culture, genetic markers, and direct gene transformation.

Tissue culture technology makes it possible to grow and maintain cells separately from the plant. This has greatly enhanced control over reproduction and inheritance, sped up the process of propagation, and reduced the amount of time required for field trials. In outcrossing plants, protoplast fusion was introduced to facilitate creating hybrids. Though wheat is self-pollinating and has largely eluded 'improvement' through hybridization, double haploid induction techniques were successfully developed in the 80s which greatly accelerated breeding. Through this process two haploids (male gametes) are merged, creating a fertile homozygous embryo in a single generation. (Koorneef)

Molecular biology has reoriented the perspective of plant breeding science to the molecular level, and has thus helped identify the genetic basis of physiological traits and the physiological components of yield. Molecular markers have been isolated for important single-gene traits in a variety of crop species. Similar to preceding technologies and methods, marker-assisted selection (MAS) gives the breeder a shortcut to selection, in this case because it both automates the process and allows them to pre-select populations and cull detrimental (or simply uninteresting) alleles (Koebner et al., 2003). Koebner et al. (2003) foresee that MAS could potentially enable breeders to be so efficient at mining genomes for material, that increased introgression of new germplasm (from wild relatives, for instance) will be required to maintain sufficient diversity. However, although it is "technically feasible to tag almost any gene with a microsatellite assay," Koebner et al. question the real utility of marker-assisted selection. They point out that few of the traits important to breeders are so simple as to be associated with a small number of loci, and those that are can often be identified by conventional means. "In any case," they continue, "genetic variation for many of the simply inherited traits might already be largely exhausted as a result of the decades of scientifically based breeding that have been applied to an intensively bred species such as wheat." More complex traits associated with multiple genes are being investigated using quantitative trait loci (QTL). QTL mapping and molecular markers are now being applied to help unravel genotype-X-environment interactions (koorneef); they are also increasingly being used to breed for lower-input, organic environments, although their compatibility with organic principles is contested (Lammerts van Bueren, date).

Much more controversial have been advances in molecular techniques that have enabled the direct transfer of gene material across genomes. Arguably, however, such techniques are only the latest in a continuum of increasingly reductive and rationalized breeding practices since the dawn of the 20th century. Legislation regulating genetically modified organisms (GMOs) in the EU was first established in 1990, and a wide range of related technologies has proliferated for modifying plants and animals for modern food systems (Lusser et al. 2011); indeed, for molecularly trained technicians the practice of gene transfer is rather mundane (Holmes, 2011). In addition to the conspicuous public discourse on the effects of GMOs on human health and the environment, critics have observed that GMO technology primarily serves to reinforce prevailing food system monopolies and maximize profit in existing agribusiness areas (Hogg). Research in biotech and genomics is costly and even more subject to the demand for return on investment, and is thus even more focused on a narrow set of species with well-mapped genomes, further abandoning innovation in less widely grown species. "Thus garlic, shallot, spinach, beans, celery, lentils, parsley, pumpkins, fodder beet, sainfoin, vetch, each have less than 4 varieties listed in the [French National Variety] catalog between 2001 and 2005, behind corn (686), tomato (159), winter wheat (130) or oilseed rape (108)." {Bonneuil et al., 2006} "The opportunities opened by modern biotechnology may strengthen existing trajectories (at least in the short term) as much as they may entail new ones. The development of herbicidetolerant varieties using transgenic methods is a well-known example. It employs the new knowledge to reinforce old markets." {Possas, 1994@27} American vegetable breeder John Navazio has criticized transgene technology not for its lack of utility, but because it facilitates an intensified reductionism, and more specifically the reduction of the organism to its commodifiable parts:

> The fundamental difference is that biotech breeders concentrate on developing a single, really fancy trait such as insect resistance in the case of Bt corn, or herbicide resistance in the case of Roundup Ready soybeans. They take the best soybean variety out there and pop in a gene for Roundup resistance and don't look at any other traits! Furthermore, this gene splicing has essentially ground to a halt the evolutionary process (which has been going on forever) in order to create one very selfish kind of cash-cow trait. (*(Peters, 2010), page 3*

In contrast, Navazio argues, a classical plant breeder will generally consider the whole organism and select for a complex of traits. Tensions also exist between conventional and biotech systems of innovation:

> "The new biologically based technological regime has shaken up a relatively stable status quo in the division of innovative labor in mechanically and chemically intensive agriculture, challenging intersectoral relationships and giving rise to new arrangements for generating and appropriating value from innovation as biotech increasingly attracts both young researchers and funding at the expense of public and field-based breeding programs. …Have the roles of public and private sector researchers become indistinguishable, as corporations invest private funds in projects—such as sequencing the genomes of important crop species—that could, and perhaps should be deemed as scientific public goods, while at the same time university and government laboratories make commercially valuable discoveries, such as genes, which they then privatize via patents, to be developed and marketed by private firms? Are universities and government laboratories being subsidized by the public to provide mere substitutes—of knowledge and technology? {Graff,@3}

A deskilling is occurring as well, as many students lack the experience or interest to do the applied work of breeding. Holmes (2011) quotes a scientist from a survey of biotech laboratories:

> From a pragmatic perspective, we have a hard time attracting students to do plant breeding because very few people coming in now have an appropriate background in agriculture. You can train a farmer in genetics. It's very difficult to train a geneticist in agriculture, because it is so complicated. [...] Farming is still an art, it's not a recipe, it's not a formula.

Ultimately, use of molecular technologies has accelerated the identification—and appropriation—of economically useful genes and regions, and has helped guide selection toward the very specific criteria of the industrial food production and processing system. Grain size, shape, density and uniformity are under fairly straightforward genetic control; they are important determinants of yield and thus market value, and have driven selection in modern wheats (Gegas et al. 2010); modern, molecular breeding has intensified the increase in grain size noted throughout wheat's history, QTLs have been identified that affect phenotypic variation in grain length and width, and due to selection for uniform shape, has contributed to reduction in shape variation (Gegas et al., 2010); for instance wider and shorter (spherical) grain is theoretically the optimum shape for maximum milling yield (Evers et al. 1990, as cited in Gegas et al., 2010).

The rise of biotech has accompanied the continued consolidation of farms in Europe into larger and larger holdings, along with technological and energy-intensification of agricultural practices. In Denmark the number of farms has decreased from 148 000 in 1970 to 47 000 in 2006, and the number of farms with more than 100 ha has gone up from 1611 to 8255 (Danmarks Statistik, 2006). "The large area at each farm creates a demand for a high efficiency in field operations" (Schjønning et al.) Precision Agriculture (PA)—the application of digital geographically referenced data in farming—has emerged to meet such demands, and comes at a cost accessible to only the largest agribusinesses entrepreneurs (Wolf and Wood 1997). PA systems are heavily engineered and can include yield sensors, field sensors, soil sensors, crop sensors, anomaly sensors, variable-rate agro-chemical applicators, automatic guidance systems, robotic harvesting systems, satellite-based remote sensing and GIS applications (Zhang et al 2002).

The same forces have also affected the economy and structure of breeding firms. Increased centralization of plant breeding and the intensive capital costs of high-technology methods continue to disenfranchise independent breeders, and force existing firms to focus on larger markets and broader adaptation. In Denmark the development of a new wheat variety costs around 7 million DKK (940,000 EUR) per year, and since a market success is only expected every four years, each successful variety must earn at least 28 million DKK for a processing company (Tybirk, 2010). This means in practice that the variety must be grown on an absolute minimum area of 100,000 hectares in order to earn a return on investment (incidentally more than double the area under organic cereal production in 2009). This trend across Europe has led to fewer and fewer agricultural crops being bred in their home regions, as well as the rapid structural development of fewer but larger processors which operate across national borders (Tybirk, 2010).

Seed System Institutions in the EU

As alluded to in both the initial interviews with breeders and the preceding account of historical trajectories, breeders' technological choices are interdependent on and structured by the sphere of formal seed supply institutions. Plant varieties—the culmination of breeders' efforts—are disseminated through a complex framework of regulatory mechanisms that has co-evolved with technologies and markets throughout the past century, one which connects and preserves the interests of multiple stakeholders in the EU: national governments, international commodity markets, seed producers and growers, food processors, agribusiness interests, and breeders themselves. The main gateway between the breeder and the market is the National List of each EU member state, which legally permits the variety to be multiplied, certified for purity, and marketed to farmers. To be eligible for the List, the variety must first pass through quality control trials to test its Value for Cultivation and Use (VCU) and Distinctness, Uniformity and Stability (DUS). The function of these related mechanisms is to protect breeder innovations, ensure optimum economic return for farmers, and ensure quality and uniform output for the market. This chapter describes the features of this network and explores how they support or constrain innovation for sustainable farming systems (illustrated in **Figure 6**).

NATIONAL LIST

Under the National List system, breeding firms submit a candidate variety to a review board with a precise variety description along with data showing results of performance trials. Members of the board include other breeders, plant pathologists, entomologists, extensionists, and representatives of regional and international seed trade associations, certification agencies, crop science societies, council of commercial plant breeders. In the 1970s, the National Lists were joined together in the European Community Common Catalogue.

While the lists were intended to standardize variety names and facilitate trade across markets, fairly quickly they had the "unintended consequence of drastically reducing the number of cultivars grown…and impinging on the ability of farmers to grow older varieties or landraces not present on the list" (Vetelainen et al. 2009). The UK for instance has seen a steady decline in the number of maintained landraces since it joined the European Community in 1973, although the country retains a number of 'heritage" varieties such as local forages, long-straw wheats used in thatching, and several potato varieties which are maintained by small seed growers associations (Vetelainen et al. 2009). Farmers in many countries still exchange home-saved seed, but it is illegal to sell it.

DEROGATION FOR CONSERVATION VARIETIES

In apparent recognition that seed regulations have affected crop biodiversity and restricted niche markets, in 1998 a new directive (98/95/EC) was introduced that amended several previous directives and established an exception for the propagation

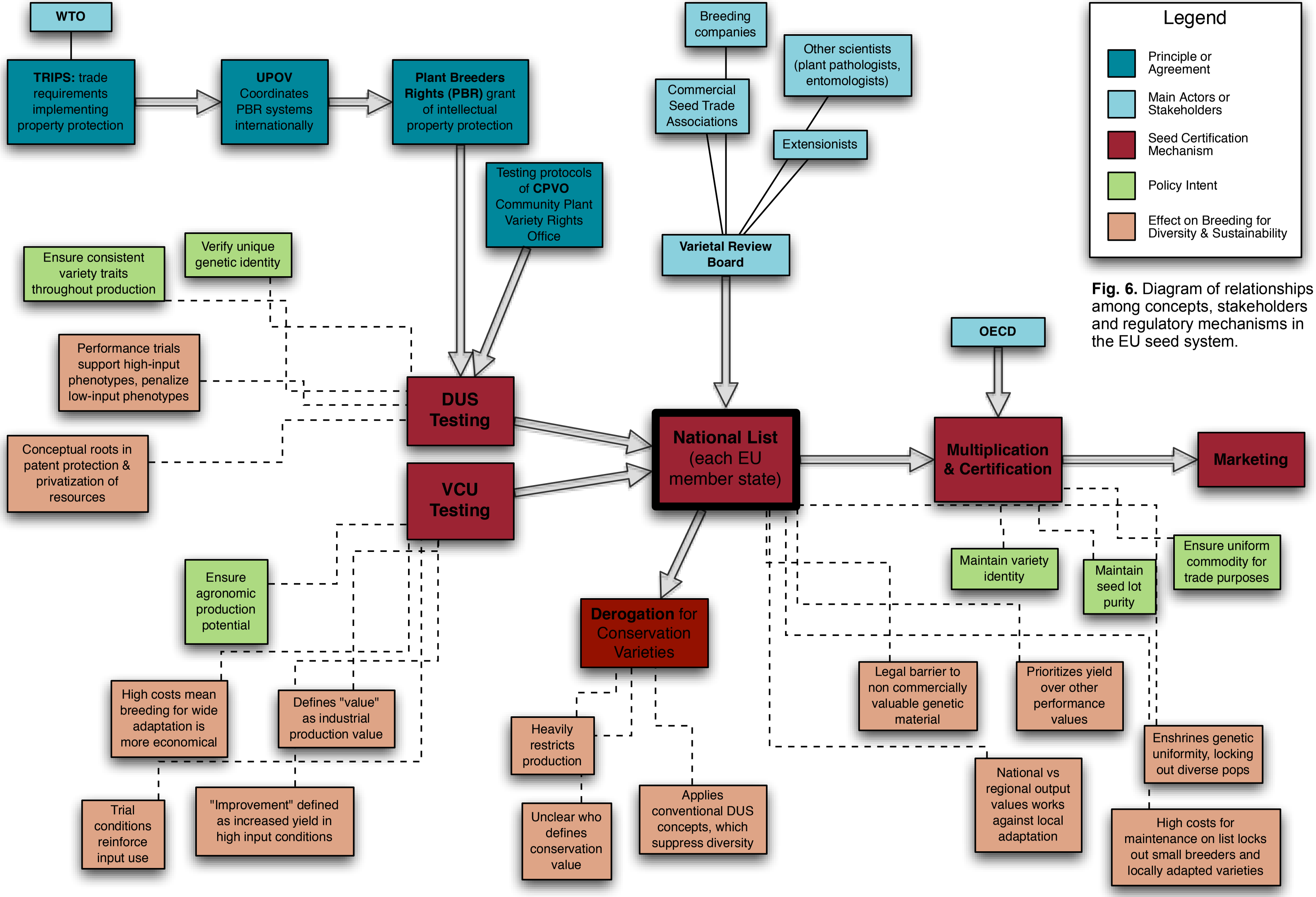

Fig. 6. Diagram of relationships among concepts, stakeholders and regulatory mechanisms in the EU seed system.

and exchange of varieties (often landraces) that are not included in national (and EU) lists. The momentum to apply it in member states has been variable and slow (Bocci, 2009). While the stated aim of the directive is to support the use and conservation of genetic resources, as Louwaars et al. (2009) point out in a detailed analysis, many key requirements serve to inhibit such use in practice. The directive for example severely restricts the quantity of seed that can be marketed (e.g. wheat) to no more than .3% of the total area for that species, which at minimum may prevent the necessary quantity for variety maintenance; production is also restricted to the region of origin. The requirements for use value are relaxed, however, for example yield potential may be lower. But the planned certification process imposes high costs that are disproportionate to the scale of production, and overall the derogation applies concepts developed for conventional seed testing which conflict with the nature of such populations, such as stability and uniformity, when for example "identifiability" may be more appropriate.

> Fixing such varieties on the basis of a description using the extensive list of characteristics seems illogical since the best contribution to in situ conservation would be to allow (or even stimulate) the continued evolution of these varieties in their changing environments, thus focusing more on identifiably (distinctness) rather than uniformity and stability of landraces. (Louwaars et al., 2009)

Anders Borgen, a Danish plant pathologist and independent organic cereal breeder agrees, stating that in practice the new derogation is so restrictive that it reinforces the use of industrial seed (Borgen, 2009). In Denmark the source material must come from the national gene bank, where they are already preserved, so the program essentially amounts to extended in-situ conservation. A new legislative orientation unique to the character of heterogeneous varieties will be required to support their use and maintenance.

DUS TESTING

As discussed previously, the concepts of Distinct, Uniform and Stable arose in the context of rapid economic development in Europe, the intense rationalization of agricultural production, and advances in plant breeding technologies which enabled increased precision over inheritance of economic traits. The function of DUS testing today remains the establishment of the genetic stability and identity of a variety before it is released to the market. In a biological system such as a crop plant, this involves the imposition of a static conceptual framework onto an inherently dynamic organism. The *distinct* aspect of the protocol shares concepts with patent law, which requires an invention to be distinguishable on some trait in order for ownership to be established. Due to a qualitative reduction in the genetic base of many commercial crops and the increase in the number of varieties, in practice varietal identification is becoming a challenge, and molecular tools are becoming more attractive for measuring distinctness {Ravishankar,@3667}. During DUS assessment a sample of candidate plants is grown in field plots or greenhouses, then its behavior and traits are recorded and evaluated for differences against existing varieties that are held within a reference collection. {Jones,@175} *Uniformity* in the behavior (such as time to maturity or seedling vigor) and morphology (such as seed size or height) of a variety is a crucial parameter for mechanized farming. Uniformity is also an important factor in maintaining varietal identity during certification, and is often considered synonymous with being genetically identical. *Stability* refers to the stability of essential characteristics over repeated reproduction; in practice however stability requires a long time to measure, so genetic uniformity is often used as a proxy (Mcguire). Together these parameters form the basis of Plant Variety Protections.

By its definition, the DUS framework prevents entry to the National List of any non-homozygous variety, irrespective of whether the variety has other performance values. A non-hybrid, open-pollinated, drought resistant maize variety with multigenic, durable disease resistance would simply flunk the exam.

> If such populations are to be used in practice, it is clear that they would not fit into the current legislative system for registration of plant varieties since they are designed, effectively, to operate in the opposite direction

> from the needs of the DUS system. Their performance across different environments depends on rapid shifts in their genetic complexity and constitution: there are, deliberately, no constant, stable or unique defining features. Consequently, if such an approach is considered to have potential value in a future of rapid environmental change, then we need to develop an alternative system for their legally defined use in practice to provide security for both the breeder and the farmer. WOLF SUSVAR

In the UK, researchers have been discussing with officials a simple alternative to DUS, which would be focus on traceability, together with VCU information. From such a register, any purchaser of seed would know: which parents were incorporated in the population, and when, how that incorporation was achieved and the environments to which the population had been subjected during its evolution."

VCU TESTING

VCU (Value for Cultivation and Use) testing involves a series of performance trials that evaluate a variety on the basis of yield, resistance to pests and disease, uniform behavior in response to crop conditions, and product quality characteristics. The trials are designed to ensure consistent agronomic performance under conditions of standard agricultural practice and to help reduce the complexity for farmers in evaluating potential varieties. To earn a place on the list the potential new variety must score higher than the average scores of the best current varieties, for the total of agronomic characteristics; for many cereals including wheat only a small percentage of varieties are admitted each year.

It may be self-evident that as the trials are based on conventional management regimes, they have the effect of rewarding the performance of conventionally-bred varieties (selected under the same conditions) and penalizing varieties bred under, for example, organic conditions. Some researchers have argued that modern conventional cultivars have the best yield potential even in low-input conditions (an effect labeled “spillover,” Cleveland, 2001), but numerous trials have shown differential responses of organic varieties in conventional tests, and vice versa (Lammerts van Bueren et al., 2008) As the dominant metric is gross yield, conventional testing often rejects cultivars with other agronomic value such as disease resistance (Vanloqueren and Baret, 2008). In addition, many of the plant traits that may confer a performance advantage in organic systems are not measured. A less dense spike, for example, contributes to a dryer canopy, decrease fungal intensity and thus increase total productivity (Konvalina et al., 2009)(See also **Figure 5**); and in conditions with lower fertility and herbicide protection, early seedling vigor is important. Researchers in the Netherlands have found that existing VCU standards have impeded the introduction of organic varieties and are therefore a disincentive to their development (Osman 2003). Varieties with slightly lower yield have been rejected, for instance, even though they had high disease resistance and would have fit well in an organic regime. VCU standards specific to the organic industry have been proposed in several countries that assess the best performers in low-input conditions (Osman). VCU testing is also expensive and poses a disproportionate barrier to organic breeders whose markets are smaller.

SEED CERTIFICATION

Once a variety has passed VCU and DUS testing and been placed on a National List, the breeders' stock of pure seed is eligible to multiplied and marketed and sold to farmers. This process is governed by the Organization for Economic Cooperation and Development (OECD) seed certification scheme, established in 1958 to harmonize seed trade rules among 58 participating countries and thus facilitate the flow of seed in international commodity chains. Certification provides important guarantees to the farmer that the variety's identity (matching the official description and resulting from a defined genotype) and purity ("proportion of plants or seeds within the population that conforms to the official description of the variety" - low percentage of off-types). It also enforces a standard of quality of seed inputs into the agribusiness production chain - that is, seeds that are free from disease, will produce healthy seedlings, and will reach a consistent and predictable yield potential under conventional production conditions. It specifically sanctions scientifically-bred seed and acts as an enforcement mechanism for plant breeders rights (OECD, 2011).

Breeder-developed seed proceeds through several classes of multiplication which ensure varietal purity is maintained. Small lots of pure, original seed (Pre-Basic) are multiplied over several generations to produce Basic seed and ultimately sufficient quantities of Certified 1st generation or Certified 2nd generation seed, which is supplied to farmers. Off-types and weeds are carefully rogued in the field, the harvest dried and cleaned, and fungicidal seed-dressings applied for storage. This process must enforce strict re-selection on breeders' varieties; over time and without careful isolation from other populations, the variety will naturally tend toward diversity due to natural processes of introgression and mutation, and the breeder's claim to that unique variety will be lost.

As with DUS and VCU testing, fertilizer and crop protection regimes endorsed by conventional agriculture are used throughout the multiplication process. The assurance of uniform seed performance has obvious value for farmers and commodity chains; as discussed previously however, intensive input regimes obscure the performance of varieties better suited to lower-input conditions, and their application during certification serves as a final barrier to entry to the market. OECD regulations do not in any way address environmental sustainability of cultural practices or appropriate input use; for example, wheat after wheat is allowed during multiplication, as long as varietal purity can be maintained (OECD, 2011), even though this practice increases disease intensity and encourages higher fungicide use (Heier et al., 2005). Unfortunately, organic seed-production conditions mean that there is increased risk of both pathogen and weed infestation which can affect seed hygiene and purity, and this is an area that requires more research and development (Steven et al., 2004). In addition, the conditions of multiplication—continuous enforcement for pure lines—pose conceptual problems for open-pollinated populations in which evolutionary processes are an accepted trait, not a "defect" to be selected against. Germination tests for example require synchrony in germination timing, which can be more variable in diverse populations.

PLANT VARIETY PROTECTIONS

Intellectual property concerns have surrounded innovations in plant material since the earliest notions of genetics at the turn of the 20th century (Dunwell, 2005). Plant variety protection systems co-evolved with advances in plant breeding technology that facilitated cloning, controlled heritability and appropriation of genetic material (Hogg). They matured in Europe in 1961 with the first formation of UPOV (Union Internationale pour la Protection des Obtentions Végétales), a trade agreement unique to plant breeders, and subsequently the TRIPs (Trade-Related Aspects of Intellectual Property Rights) Agreement, a treaty administered by the World Trade Organization (WTO). The premises for granting legal protection to plant varieties is to protect against exploitation from competitors, and to support investment in R&D by ensuring that breeders can recoup the costs of their investments.

Although plant variety protection has a conceptual basis in industrial patent protection, innovations on life forms are only possible through physical access to existing forms. Plant breeders have long enjoyed what is called a *breeder's exemption* - the right to access the material for research purposes. Among breeders therefore there is a history of fairly free exchange of germplasm, especially among wheat breeding programs (Heisey, 2002). Yet, with the boom in biotechnology and accelerated privatization of germplasm in the 1980s, there was a trend toward increasing restriction on exchange of material: Amendments to the terms of UPOV from 1978 to 1991 include an extension on the period of protection from 15 to 20 years for most plants; the breeders' exemption was limited; and "farmers' privilege" was circumscribed (Helfer, 2004). Today, some of the world's largest biotech firms want to implement a phased-in exemption which would require competing breeders to wait 10 years before accessing the material. Numerical simulations (Eaton, 2005) predict that curtailing the breeders' exemption may drive competitors out of the market—in an industry already notoriously monopolistic—due to an "asymmetrical increase" in competitors' costs to innovate without infringing on the protection. Furthermore, Eaton and van Tongeren (2005) suggest that the protection would give the leading firm little incentive to increase investment, while varietal quality and farming sector profits would decrease. Intellectual property rights are a pivotal and controversial factor in the use of biotechnology innovations in wheat, where there have been cases of private firms trying to obtain IPR for varieties developed from freely shared germplasm (Heisey, 2002).

There has been a notable convergence of the aims of biotechnology and plant variety protections, and more recently patent claims. The granting of breeders rights is increasingly contingent on the ability to verify the distinctness of a variety at the molecular level against large reference collections (Jones), and in a sense, the proposed use of markers during registration to solve the 'problem' created by increasing phenotypic similarity (Röder et al 2002) reflects a circular logic. Furthermore, as molecular markers and other techniques are amenable to high-throughput automated analysis, they are likely to accelerate data-mining and the private accumulation of genetic reference material:

> The possibility of creating a functional super-database that would allow one to know which consumers want which products and be able to shuffle genes to produce such a product and then deliver it accompanied by a comprehensive pedigree represents a powerful incentive to pursue private development of such a database as a substitute to sharing information in public reference networks. (Allaire)

Intellectual property protections in their current form are largely immaterial to the situation of genetically heterogeneous variety mixtures and open-pollinated or evolutionary populations. This poses a challenge to independent breeders developing such material, as traditional royalties that accrue to breeders when seed as purchased may not apply. Interestingly, populations in particular may provoke a re-evaluation of the role of the breeder versus the farmer in developing and maintaining varieties. Martin Wolfe of Elm Farm Organic Research Centre in the UK, writes:

> [Evolutionary] populations are, of course, modified in each growing

> season whether the grower is a breeder or a farmer, and irrespective of whether or not there is any form of imposed selection. Indeed, it can be argued that even if a population sample is held in store for one season, it will represent a different selection potential against a new environment than a sample of the same population which had not been stored. In other words, although the breeder may have a primary function in generating a population in the first place, subsequent development of the population may be regarded equally as a function of the farmer. These different activities need to be recognised in relation to rights.
>
> In this sense, the major role of the breeder could be recognised by a license for initial production of a particular population and the right to charge a royalty fee for initial cultivation of that population (e.g. for the F7 only, or for a later generation to allow for the breeder's initial seed multiplication). Wolfe (2008)

Due to the endless possible forms of a population that could emerge following release, Wolfe proposes graduated royalties based on varying degrees of use and manipulation by the farmer. Karl-Josef Mueller, a cereal breeder for organic and biodynamic farms in Germany, suggests first of all that the financing of breeding should be done by private breeding foundations; then the breeder and breeding facilities are paid when the new variety is created and before its use begins, and no additional protections would be needed, except to exclude it from copying by others (Personal communication, July 14, 2011).

Case Study: Agroecosystem Effects of Reduced Nitrogen Use in Denmark

The case of nitrogen fertilizer regulation in Denmark provides a final illustration of the feedback effects of institutional selection on the trajectory of variety development as well as the structure of the local seed industry. Beginning in 1987, Denmark introduced several progressive restrictions on the use of applied mineral N in agriculture, under its Action Plans for the Aquatic Environment (part of EU water directives aimed at reducing nitrogen leaching to the sea and groundwater); improved utilization of N from animal manures was also instituted (Grant & Blicher-Mathiesen, 2004).

Though their implementation was more difficult and took much more time and monitoring than policy designers expected, the regulations have had the intended impact. Since the introduction of these programs, the calculated nitrogen leaching from the root zone on agricultural land has decreased by 33% (1989–2002), and nitrogen loads draining agricultural catchments have been reduced 32% (Kronvang et al., 2008).

EFFECTS ON YIELD

An important policy change that occurred alongside the restriction was the shift in focus from gross yield to net yield, or economic optimum, when determining allowable application rates of nitrogen and other chemical inputs. The economic optimum is defined by the Danish Ministry for the Environment as the rate at which the cost of applying more fertilizer would exceed the economic value of the increased crop yield. Application "norms" were then set progressively as a percentage of the economic optimum; by 2006, applied N was restricted to 86% of economic optimum (Petersen et al., 2010). The same principle, applied to fungicides, led to the widespread use of reduced fungicide dosages. While the reduction in N use led to a net reduction in gross yields of wheat up to 4-5 dt/ha (Petersen et al., 2010), and up to a 1% loss of crude protein content (Tybirk, in press), farmers nevertheless have come to view the impact on their economies as minimal. It is important to note that most (70%) of the wheat crop in Denmark and other Western European countries is used for pig feed, and for this purpose wheat is primarily a source of energy (starch). Farmers growing certain bread wheat varieties on a contract with millers face different market requirements, and can get a dispensation to use the "normal" amount of nitrogen.

The restricted N rates phased in in 1993 and 1999 have been perceived by some stakeholders as the main cause of reduced yields and reduced yield potential seen during that time. In a study of the effects of environmental, genetic and management factors on yield of winter wheat from 1990-2006, Petersen et al. (2010) found that only a small part of the yield stagnation observed in Denmark could be attributed to reduced N rates – less than a third of the effect of breeding. Furthermore, Petersen et al. observe that Belgium, Germany, France, Netherlands, Sweden, UK – nations with higher average N application rates - have all seen yield plateaus beginning at the same time in the mid-1990s, and attribute this to environmental changes as well as number of agroecological factors including soil tillage, soil compaction and farm management.

EFFECTS ON BREEDING

Erik Tybirk, an independent Danish scientist with 30 years experience breeding cereals and oilseeds in Scandinavia, discussed several important consequences of the nitrogen reduction on breeding for wheat in Denmark (Tybirk, 2011). As nitrogen is the most limiting nutrient for winter wheat production, the changes had a direct effect on demands on breeders to develop varieties with better root development and a better ability to exploit available nitrogen. Contrary to the prevailing assumption that high yield in optimal environments will "spillover" into production in marginal environments (Cleveland, 2001), the best cultivars for Danish lower-nutrient conditions have proven to be those bred in similar environments:

> "This reflects the fact that selection under low N conditions will over time adapt the varieties to low N conditions. This is really the only realistic explanation. Examinations on root development in the more recent Danish cultivars have not yet proven it, but some tests suggest these varieties to have a better root development in the autumn (which reduces the winter leaching of nitrogen down towards the groundwater)." (Tybirk, 2011)

The regulations essentially transformed Denmark into an "island" of lower-nitrogen conditions compared to surrounding countries.

> "Our varieties are growing taller, because if you make the plants shorter, you cannot have competitiveness against weeds – so in Denmark we move automatically in that direction because we are forced to make the

> yield OK in this environment… Every time we get visitors from Ireland they laugh at us, at our tall varieties, 'You are not using X type of growth regulators… it's ridiculous not to do that'; and these short English varieties, often they fall out early in trials in Denmark because they are not stress-resistant. [For example the variety] 'Savanna' yields well in New Zealand where they put 350kg N, but it always falls down in yield in our testing here." (Tybirk, 2011)

The unique situation in Denmark has made it difficult to select foreign varieties for Danish conditions, and as a result Danish-bred winter wheats have reclaimed a significant competitive advantage in the domestic market compared to foreign-bred material. Based on data from country trials from 1991-2010, the number of Danish-bred varieties represented in the top-selling varieties rose from just 10% in 1991 to over 60% by 2010 (**Figure 7**). Likewise, Danish-made varieties are no longer as competitive in England and Germany because other varieties do better under the more intensive conditions. In this case, differentiation in target environment led to the reemergence of "local" seed in an era of entrenched globalization.

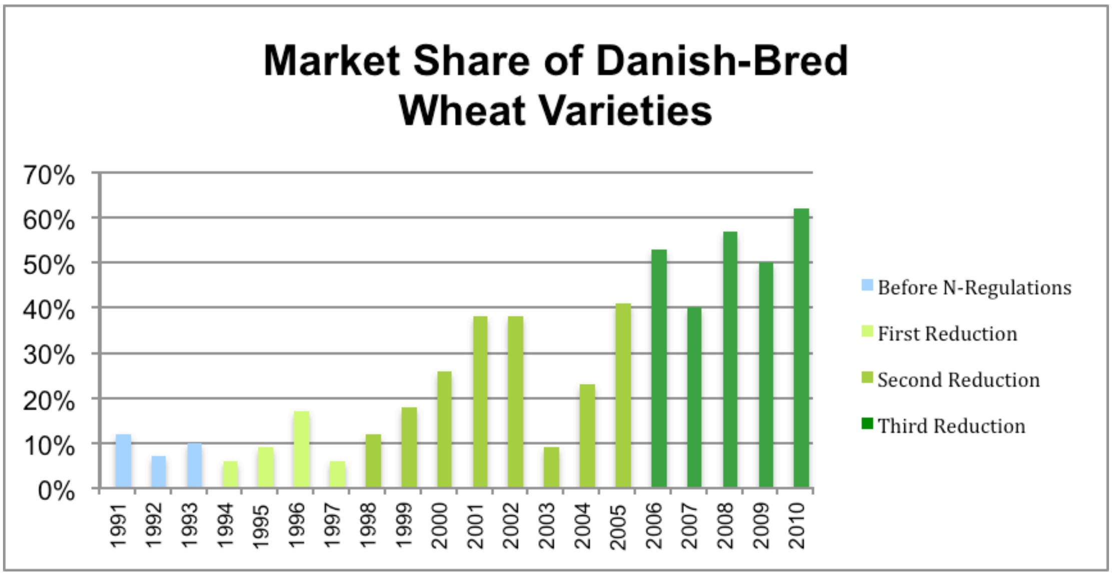

Fig. 7. Data from Tybirk (in press)

The potential benefits of the growing conditions in Denmark are recognized in neighboring countries. One of the conventional breeders interviewed in Sweden stated that they are looking into developing more nitrogen-efficient varieties in order to implement new sustainability goals into their program, and that having trials in Denmark works well towards that because there would naturally be a pressure in that direction.

> “It’s interesting to see that there are definitely lines that are more nitrogen efficient than others, and what a shame not to use it. If we can put 140 kg of N on 100 000 ha instead of putting 160, it’s such a gain. … In the end it has to be driven by economy, so if the N is more expensive, then you look into varieties that are more efficient.”

Conclusion

> Where we go next depends on where we are now and where we have been. (Maréchal et al., 2008)

This research highlights several important bottlenecks to the development of more sustainable crop cultivars in Western Europe and Scandinavia. Institutional, historical, individual, technological, and historical and cognitive factors have interacted in the last century to create a trajectory in plant breeding with unlimited economic growth as its organizing principle, in contrast to an approach that values sustainable use of finite resources. This dichotomy occurs in multiple domains: for instance between a focus on the whole system in agroecology versus the reductive focus on single components; or between knowledge-based and fossil-energy based regimes; or, finally, between the values of industrial commodity chains versus the values of civil society. This dichotomy is summarized below in **Figure 8**, highlighting a suggested “sustainable” point of technological intervention.

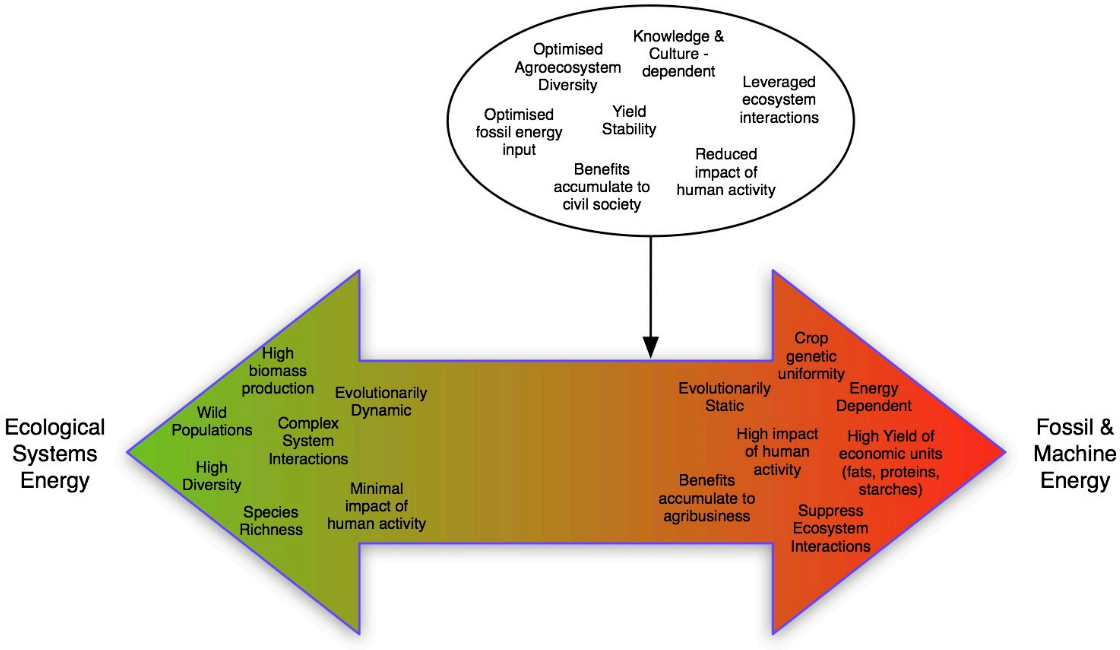

Fig. 8. Conceptualization of a spectrum of energy use applied to agricultural systems, showing proposed point of agroecological intervention

In the current study, institutional selection appears to be acting most heavily to shape the technological choices of breeders and farmers, thus it is at the institutional and policy level where effort must be directed if a shift is to be made away from productivist values to sustainable ones. Improvements to the variety registration framework to accommodate heterogeneous varieties would benefit the agricultural procuction system in Europe in multiple spheres; it would diversify fields, markets, and ecosystems; it would decentralize control over breeding and germplasm; it would reorient the modern relationship between the breeder and the farmer; and lastly it would support the technological innovation in the direction of more sustainable plants.

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