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Is plant breeding science objective truth or social construction? The case of yield stability

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Abstract. This article presents a holistic framework for understanding the science of plant breeding, as an alternative to the common objectivist and constructivist approaches in studies of science. It applies this approach to understanding disagreements about how to deal with yield stability. Two contrasting definitions of yield stability are described, and concomitant differences in the understanding and roles of sustainability and of selection, test, and target environments are explored. Critical questions about plant breeding theory and practice are posed, and answers from the viewpoint of the two contrasting definitions of yield stability are analyzed, based on key publications in the field. Differences in answers to these questions appear to result both from the contingencies of plant breeders' experiences with particular crop varieties and growing environments, and from differences in social and institutional settings – plant breeding science is both objective truth and social construction. The goal of using a holistic framework is to encourage discussion among plant breeders, farmers, social scientists, and others, of the bases for disagreements within plant breeding, in order to facilitate plant breeding's contribution to a more environmentally, economically, and socially sustainable agriculture.

Key words: Crop genetic resources, Epistemology, Genotype-by-environment interaction, Green Revolution, Modern crop varieties, Plant breeding, Scientific knowledge, Sustainable agriculture, Yield stability

Abbreviations: CGIAR – Consultative Group on International Agricultural Research; CIMMYT – Centro Internacional de Mejoramiento de Maíz y Trigo (International Maize and Wheat Improvement Center), Mexico; CV – coefficient of variation (standard deviation/mean × 100); FV – farmer crop variety; G×E – genotype-by-environment interaction; MV – modern crop variety; OPV – open pollinated crop variety

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Introduction

Plant breeding has been an essential part of agricultural development from the first plant domestications about 12,000 years ago and the subsequent spread of new crops and crop varieties around the world, to the advent of modern, scientific plant breeding 100 years ago, the Green Revolution 40 years ago,[1] and today's biotechnology revolution.

Farmer plant breeders (hereafter simply "farmers") have been responsible for the development of thousands of crop varieties in hundreds of species (Harlan, 1992). The local crop varieties developed by farmers (*farmers' varieties* or FVs, which include traditional, local varieties, also referred to as landraces, and locally adapted progeny from crosses between these varieties and modern varieties), are usually defined as having narrow geographical adaptation to relatively *marginal* (high stress, variable) growing environments,[2] and relatively low yield and high yield stability in those environments from year to year (Harlan, 1992; Zeven, 1998).

Plant breeding as a specialized activity began about 200 years ago in industrial countries, and its importance relative to farmer breeding has increased steadily (Simmonds, 1979: 11–13). Modern, professional plant breeding developed in the early part of the 20th century, based on Darwin's theory of evolution through selection and the genetic mechanisms of evolution elucidated by Mendel and others, and ultimately led to further separation of farmer and professional breeding (Allard, 1999: 24–25; Simmonds, 1979) and seed supply systems (Cromwell et al., 1993). The emphasis of most professional, scientific plant breeders (hereafter simply "plant breeders") has typically been on developing a relatively small number of genetically more uniform *modern varieties* (MVs), adapted to geographically wide, relatively *optimal* (low stress, uniform) growing environments,[3] with high yield and yield stability in these environments (Evans, 1993; Fischer, 1996; Frankel et al., 1995). Modern agricultural development, in which plant breeding plays a major role, has achieved remarkable success in increasing food production to meet the demand of a growing population (Evans, 1993; Evans, 1998).

Today, however, agriculture and plant breeding, like most human activities, are facing unprecedented challenges at both local and global levels. It is widely agreed that human impact on the Earth's ecosystems threatens the current patterns of biological and sociocultural diversity, and this has focused attention on achieving more sustainable human-environment interaction (Vitousek et al., 1997), including agriculture (Matson et al., 1997). At the same time, the demand for food is increasing, while past approaches to increasing food production are often considered to be inadequate (Evans, 1997; Mann, 1999).

Plant breeding for sustainable agriculture means increasing yields (amount of edible harvest per unit of land) in both

(a) environments that have been optimal and high-yielding, but where stress on plant production is increasing as inputs are being reduced to reduce production costs and negative environmental impacts, and
(b) environments that are marginal and low-yielding, those of many of the world's farmers who have not adopted MVs, but whose FVs often have inadequate yields (Callaway and Francis, 1993; Ceccarelli, 1996b; Cooper and Byth, 1996; Evans, 1997; Fischer, 1996; Heisey and Edmeades, 1999; Hildebrand, 1990; Sleper et al., 1991).

As a goal of plant breeding, the stability of yield is often considered to be of equal importance to yield itself (Anderson and Hazell, 1989c; Federer and Scully, 1993; Pingali and Rajaram, 1999). *Yield stability* is a measure of the variation in yield of a crop variety over different environments in comparison to other varieties. It is a special case of *genotype-by-environment interaction* (G×E), defined as the degree to which different genotypes[4] (or varieties) behave consistently across different environments (Hill, 1975). The two most important factors affecting G×E for yield of a crop variety (and thus its yield stability), are the degree of similarity between the environment where it is selected or tested and the environment where it will be grown (target environment), and the level of genetic diversity of the variety[5] (Hill et al., 1998: Chap. 7). The role of yield stability and its relation to yield is a very controversial topic in plant breeding, and one that is critical for understanding how to make agriculture more sustainable.

This article explores the use of a holistic approach in the study of plant breeding science to understand the extent to which disagreements over the definition and use of yield stability can be understood as the result of differences in the plants and environments plant breeders work with, or differences in the social and institutional contexts in which they carry out this work.[6] The overall question I address is stated in the title: "Is plant breeding science objective truth or social construction?" To answer this, I pose the following more specific questions: 1) "How do differences in understanding of what sustainable agriculture means influence the definition of yield stability?" 2) "How do differences in the definition of yield stability used by plant breeders affect their understanding and choice of selection, test, and target environments in their development of new crop varieties?" 3) "How does the choice of selection, test, and target environments affect the yield stability of the crop varieties they produce, and thus the sustainability of agriculture?" and 4) "How can similarities and differences in plant breeders' understanding of yield stability, and choice of selection, test, and target environments be explained as the result of both similarities and differences in biophysical reality and in the social reality on which knowledge is based, and in the epistemological process of its production?" My goal here is to stimulate discussion of disagreements about yield stability, and research on the causes of these differences, in order to clarify the role of yield stability in plant breeding and sustainable agriculture.[7]

In the following section I describe the common approaches (objectivist and constructivist) to understanding plant breeding, and the holistic alternative I take in this article. In the next section I describe yield stability and two contrasting definitions of this important concept used by plant breeders, and their relationship to sustainable agriculture. The next section examines these two definitions in terms of the relationship of yield stability with selection, test, and target environments by posing critical questions about plant breeding theory and practice. I highlight the major differences in answers from the viewpoint of the two definitions, based on key publications, and explore the extent to which both the commonalties and the unique contingencies of the particular genotypes and growing environments plant breeders work with, and of the social/institutional settings within which they work, may explain similarities and differences in knowledge and practice among plant breeders.

Plant breeding science: Objectivist, constructivist, and holistic approaches

Much of the current intellectual discussion about the nature of "reality" and of scientific knowledge is polarized between objectivist and constructivist camps (e.g., Gould, 2000; Harding, 1998; Hull, 1988).[8] The assumption at the *constructivist* end of the spectrum is that knowledge is dominated by social forces, including power relationships, and is historically and culturally particular (e.g., Foucault, 1994), i.e., the process that mediates the acquisition of knowledge (epistemology) is dominated by preexisting knowledge, including values, acquired through participation in a particular institutional or social setting, often mediated by the social control of technology and information. The assumption at the *objectivist* end of the spectrum is that more and more universal and accurate knowledge of biophysical reality is a valid goal, i.e., epistemology is dominated by scientific methods capable of discriminating and eliminating social influences and of ascertaining the true nature of the world outside the individual mind (e.g., Wilson, 1998). A holistic approach is an alternative to these predominant views, often irreconcilable by definition, and sees scientific knowledge as both an important way of increasing objective knowledge of reality, and as a social process that reflects the particular cultural and political environments in which it operates (Bourdieu, 2000; Gould, 2000; Harding, 1998; Hull, 1988).

Figure 1 is a simplified model, using terms and concepts found in the current literature, of the possible relationships between objective biophysical and social reality, epistemology, knowledge, practice (behavior), and the effects of practice on biophysical reality. Epistemology[9] is defined in this model as the process by which stimuli from the external physical world (e.g., from stars, wheat plants, yield trial data, journal articles, a colleague's verbal comments) are first received and then processed into physical patterns within a person's brain, which may subsequently be perceived subjectively as knowledge, or may remain unconscious. This process is influenced by the biological structure and function of the brain,[10] the languages, technologies and practices used, and by preexisting knowledge and thought processes.

Most studies of plant breeding have been from either an objectivist or constructivist perspective, including treatment of theoretical disputes within plant breeding, although these disputes have for the most part been ignored. In the following subsections I outline these two approaches to understanding plant breeding science and controversies within it, and the holistic alternative I use in this article. Figure 1 also includes the corresponding variables for plant breeding in brackets.

Objectivist approach

In an objectivist approach plant breeding science is often seen as increasing the amount and accuracy of objective knowledge about plants and their environments through testing of theory-based hypotheses, and applying this knowledge to produce new, more desirable crop varieties. The objectivist approach is taken by most plant breeders. Plant breeders consider themselves to be "applied evolutionists" (Allard, 1999: 49; Simmonds, 1979: 27) and text books document the development of the profession after 1900 through the application of Darwinian theories of natural selection and evolution,[11] together with the basic mechanisms of inheritance and expression of the phenotype[12] (via G×E) discovered by Mendel in 1885 and rediscovered and elaborated by others in the first decades of the 20th century. The development of theory and its application to practice continues to be an important plant breeding activity, for example in understanding and dealing with G×E by combining statistical and quantitative models of plant breeding with biophysical models of agronomists (Cooper and Hammer, 1996b), or in understanding yield and how to increase it through a whole-system vs. the common reductionist approach (Wallace and Yan, 1998).

However, plant breeders also recognize that their theoretical understanding of plants is limited by the lack of required experimental data, and of the technologies and resources necessary to gather it. As a result, much plant breeding has been empirical rather than theoretical, with breeders working with "a large number of unknown genotypes in ill-defined environments resulting in little understanding of G×E" (Souza et al., 1993: 197). Especially in the early stages of a breeding program when very large numbers of plants or lines must be evaluated, selection is based on "rapid visual comparison" (Wallace and Yan, 1998: 320), and "inexplicit, intuitive" selection indices dominate, with little information on G×E available, making selection

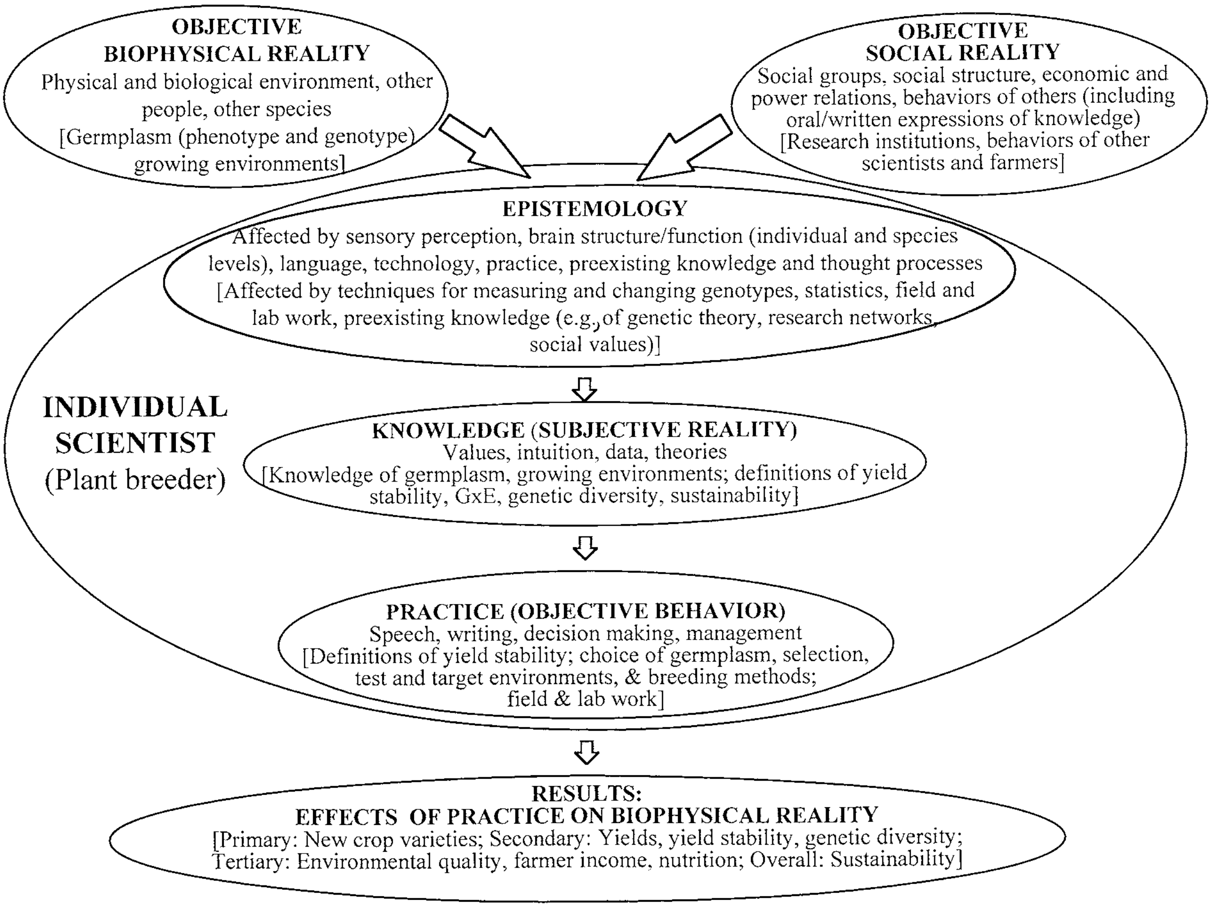

Figure 1. A holistic model of reality, knowledge and practice, a plant breeding example [plant breeding variables in brackets].

for yield stability inefficient (Simmonds, 1979). Therefore, plant breeders frequently describe plant breeding as partially an "art," based on intuition and empirical trial-and-error, as well as on theory (e.g., Simmonds, 1979; Wallace and Yan, 1998).[13] In this context they sometimes recognize that the contingencies of their experiences with specific genotypes and environments can influence their empirical understanding, and that different plant breeders can therefore differ. However, there is almost no discussion within objectivist accounts of how differences in genotypes or environments could affect theoretical knowledge.

Objectivist studies of plant breeding may also include the social setting within which plant breeding operates. Plant breeding as a whole is often seen as responsive to a social demand for improved crop production to counter hunger, as is emphasized in early objectivist accounts of the Green Revolution (Stakman et al., 1967; Streeter, 1969). A typical statement is that a "humanitarian viewpoint" "requires a focus by plant science on the inevitable need" "to feed the ever growing population of the world" by continuing to increase yields (Wallace and Yan, 1998: 336), or that increased yields are needed to buy time for society to deal with issues affecting population growth (Borlaug, n.d.).

The influence of economic factors on the kinds of activities plant breeders are involved in, including the difference between public and private plant breeding, is also recognized. This has been an increasingly central issue in discussions among plant breeders as private interest in plant breeding has grown beginning with the development of hybrid maize in the United States in the 1930s, and accelerating in recent years with the biotechnology revolution.[14] One of the key cases for both objectivist and constructivist studies of plant breeding is the choice of hybrids in the development of improved maize varieties, and the corresponding neglect of open pollinated varieties (OPVs). Hybrid maize has come to account for 100% of maize in the United States and a large proportion of maize area in the rest of the world, and the production of hybrid maize seed is a major industry. The common objectivist account by plant breeders sees hybrid maize development as the logical outcome of the application of plant science (e.g., Hallauer and Miranda, 1988).[15]

However, while objectivist accounts may recognize that social factors can influence plant breeding science in terms of where that science is applied, or who benefits most directly from it, plant breeding science itself is considered to be socially neutral – it does not determine social effects, and social factors do not affect scientific epistemology or theory.

Constructivist approach

In a constructivist approach, the development, application, and results of plant breeding science, including the kinds of crop varieties developed, are often seen to be primarily the result of macro political or economic variables, foremost among them industrial modernism. This is the approach of most social scientists who research or discuss plant breeding. For example, Scott sees the theoretical foundation of professional plant breeding as *unscientific* (i.e., not objective), and *imperialistic* in its claims to universality, influenced by the precepts of high modernist agriculture, focused completely on transforming the climate and environment to fit a predetermined "ideal plant type" (Scott, 1998: 301, 340). The "basic procedure is exactly the reverse" of that of indigenous farmers, who are seen to have a much more complete and sophisticated understanding of objective reality in the development of their crop varieties (Scott, 1998: 302). "Like the formal order of the planned section of Brasilia or collectivized agriculture, modern, simplified, and standardized agriculture depends for its existence on a 'dark twin' of informal practices and experience on which it is, ultimately, parasitic" (Scott, 1998: 270). Thus plant breeding is seen as part of the power struggle between indigenous and modern, and modern plant breeding follows the "logic" of modern agriculture, whereby if the environment can be simplified to "the point where the rules do explain a great deal, those who formulate the rules and techniques have also greatly expanded their power" (Scott, 1998: 303).

Whether plant breeders' practice is consistent with their knowledge of plant breeding (including values), in contrast to its being coerced by the institution/society in which they work, is usually not empirically addressed. However, not infrequently there is a strong implication in constructivist accounts that plant breeders have the same modernist values as are perceived to be those of the society or institution. For example, plant breeders have been characterized as continuously working at shaping the social structure of plant breeding that allows them to get away with the "negotiation, persuasion and coercion that are central to the breeding process when a new variety is being designed," i.e., first creating "as much variation as possible" then "eliminating precisely those novel, unusual variations in plants that were so interesting at first" in order to "stabilize the new variety so that it appears as if it could not possibly be otherwise, so that it appears 'natural,' " while being "*reluctant to admit the peculiar nature of their work*" (Busch et al., 1995: 28, 29; emphasis added).

Therefore, the development of plant breeding science is not the objective application of science to stave off hunger threatened by an increasing population. Perkins, for example, asserts that the major cause of hunger is unequal distribution of food, not inadequate production, and that development of plant breeding in the 20th century was strongly influenced by the dominant theory of Western political leaders in the post WW II period – that fast growing populations demanded increased food production to protect their national security (Perkins, 1997). He maintains that the promoters of the Green Revolution uncritically accepted "Malthusian pessimism" and the necessity of modernization, with the implication that subsistence agriculture and the industrial state are incompatible. He argues that plant breeding was institutionalized in Britain and the US (and to some extent in India) as part of social and political modernization and industrialization.

A constructivist account of hybrid maize emphasizes the social determination of plant breeding science. Kloppenburg, for example, says that directing maize breeding toward hybrids is an example of plant breeding science being controlled by capitalists, in order to overcome the "natural characteristics of the seed" that "constitute a biological barrier to its commodification" (Kloppenburg, 1988: 11). While the state provided public support for plant breeding through 1935, capital has since then sought to change the division of labor to capture the profits associated with the release of finished varieties, and to relegate the public sector to "basic" research. Kloppenburg emphasizes that there was no clear biological/agronomic superiority of the hybrid route, but that the tremendous effort put into research on hybrid maize, leading to its successful commercialization in the 1930s, can best be understood as the result of influence of capitalism on public agricultural research.[16]

Just as objectivist accounts tend to omit consideration of the effect of social reality on empirical, and especially theoretical plant breeding knowledge, so do constructivist accounts tend to omit consideration of the effect of biophysical reality (plants and environments), leaving much of what plant breeders see as the heart of plant breeding as a black box. According to constructivist accounts, plant breeders' epistemology is dominated not by the nature of the genotypes and environments plant breeders work with, but by preexisting knowledge, including values, acquired through participation in a particular institutional or social setting, or through the social control of technology or information (Figure 1). The details of how these social variables affect individual plant breeders' knowledge about genotypes and environments is not usually examined. Indeed, there appears to be little social science research on crop breeding strategies, including within the CGIAR's international research centers,[17] and few data exist on important theoretical issues within plant breeding such as wide vs. narrow adaptability, an important topic in the yield stability debate (Byerlee, 1994).

A holistic approach

Research on plant breeding from both objectivist and constructivist ends of the spectrum has made important contributions to our understanding of plant breeding knowledge and practice and to the historical development of plant breeding in its social and biological contexts, but each ignores essential components of the plant breeding system. In social studies of science, a *holistic*[18] approach seeks a middle ground between the two poles of "objectivist" and "constructivist." 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 (Figure 1). It is a position that "rejects both epistemic absolutism and irrationalist relativism" (Bourdieu, 2000: 111; see also Cleveland, 1998; Gould, 2000; Hull, 1988; Nader, 1996).[19]

I propose a holistic approach to the study of plant breeding science that sees as compelling the evidence on plant development and adaptation, gene function, and the influence of growing environments, compiled by biological scientists during years of observation and experimentation, that suggests a universal biophysical reality of plants and their environments (and by implication biophysical universals in human cognition), providing a systematic and generalizable framework for methods to produce desired changes in plant genotypes. This approach also sees as compelling the evidence on the history and social contexts of plant breeding, compiled mostly by social scientists, that suggests that plant breeders' knowledge of plants and environments is influenced by preexisting knowledge, including values, affected in turn by the social environment and institutions (objective social reality) that plant breeders work in. All of the major elements of the plant breeding system (listed in Figure 1 in brackets) are included in this holistic approach. It does not assume the primacy of any of them, but advocates empirical research to understand the relative contribution of all of them in any particular situation.

Especially for those aspects of the biophysical reality of genotypes and environments that are less well understood in terms of plant breeding theory, plant breeders' knowledge may more likely be based on the particular experiences that each one has with the particular environments and crop varieties they work with. This knowledge may be more the result of intuition than objective science, and thus be less generalizable, and more apt to be influenced by values and preexisting knowledge (including values) specific to the plant breeder's social environment. This means that disagreements among plant breeders could arise even though fundamental genetic and statistical principles remain constant across a range of contexts, because the "art" of plant breeding is more tied to specific individuals and/or environments (Soleri and Cleveland, 2001).

While a holistic approach to the study of plant breeding has not been well-developed, a number of beginnings have been made. Simmonds (an eminent plant breeder) notes that "serious questions about the socioeconomic role and effects of plant breeding are rarely asked and good answers are hard to give" (Simmonds, 1990: 337). What he means by "serious questions" seems to be those that relate the biological basis of plant breeding to the socioeconomic, as reflected in his subsequent suggestion that plant breeding always implies an economic advantage for someone, and that benefit/cost analysis can be combined with G×E analysis to improve plant breeding. Simmonds' takes a similar approach to hybrid maize development, citing the fact that hybrid seed has to be purchased every year as providing an economic incentive for choosing hybrid over OPV development, although considering it likely that the economic incentive was not decisive (Simmonds, 1979: 153). This is a more holistic approach than taken by most plant breeders, though not including the macro sociocultural perspective of many constructivist approaches. Hildebrand (an agricultural economist) has also argued for integrating biological and social factors in understanding plant breeding, specifically in terms of yield stability, and uses the phrase "philosophy toward the use of stability analysis" (Hildebrand, 1990: 172–173). However, he does not discuss factors in the social and institutional environment of plant breeders that would lead to a given philosophy, or the underlying values of such a philosophy.

Yield and yield stability

As discussed in the introduction, both high yield stability and high yield are very desirable goals for plant breeders, with yield stability considered especially important for sustainability. The problem comes when yield and yield stability are negatively correlated. The challenge is to understand the nature and cause of any negative correlation and how it can be reduced or eliminated. This discussion takes place in two main parts. The first is carried out primarily by economists based on yield and production data, often aggregated at national or regional levels, and for several crops, and seeks to explain production stability in terms of variation in planting patterns, government policies and markets, and inputs such as irrigation water, as well as in terms of crop varieties. The second, the topic of this article, is carried out primarily by plant breeders, and focuses on explaining stability at the plant, population, and varietal level in terms of biological variables, and achieving stability through the design and management of plant breeding programs, including the choice of selection, test, and target environments.

Yield stability in agriculture and plant breeding

Analysis of the magnitude and causes of instability of yield in agriculture as evidenced in aggregate production and yield data is contentious, in part because research results are subject to influence by a number of methodological variables, such as the choice of time periods and geographical units, the method of data transformation, and the choice of statistics for analysis[20] (Anderson and Hazell, 1989a). However, there appears to be general agreement that yield stability is an important factor in agricultural production, may be expected to increase in the future in many areas, and that the MVs developed by plant breeders may be an important factor affecting yield stability (Calderini and Slafer, 1999; Hazell, 1989; Naylor et al., 1997; Singh and Byerlee, 1990).

Better understanding of yield stability appears to be critical for decisions at every level of the agricultural system, including the farm household's criteria for selecting and adopting new crop varieties, which varieties to plant each season in each field, and how much to invest in crop production vs. other activities; the plant breeder's choice of breeding program goals, sources of genetic diversity, and test and target environments; and the government policy maker's choice of agricultural price supports, input subsidies, crop insurance, or scale of development projects (Anderson and Hazell, 1989c). How such decisions are made will in turn have major effects on sustainability.

While they are also interested in understanding the contribution of plant breeding to aggregate yield stability, plant breeders' primary interest in yield stability is in understanding how it can be effectively used as a goal in breeding, and to what extent it is compatible or incompatible with other breeding goals, such as yield, wide adaptation, or resistance to specific stress factors. Indeed, plant breeders often consider yield and yield stability to be the most important components of crop phenotype, and understanding crop phenotype as a result of G×E remains one of the foundational principles of plant breeding[21] (Allard, 1999; Simmonds, 1979), and one of its most important challenges for the future (Cooper et al., 1996; Kang and Magari, 1996; Yan and Hunt, 1998; Rosielle and Hamblin, 1981).

However, plant breeders do disagree strongly about the specific nature of the biological relationship between yield and yield stability, and the significance of any negative correlations between them, and, therefore, on the extent to which such negative correlations require changes in plant breeding theory and practice, including the choice of selection, test, and target environments. This disagreement is reflected in the different working definitions of yield stability used by plant breeders.

Defining and using yield stability

The easiest and most intuitively appealing way to present contrasting definitions of yield stability is by use of regression slopes (Figure 2), a method widely used by plant breeders.[22] The stability of individual varieties is indicated by comparison of their regression slopes over a range of environments, with each environment defined by the mean performance of all varieties in the trial in that environment,[23] so that the population mean has a slope = 1.0 (Eberhart and Russell, 1966; Finlay and Wilkinson, 1963; Hill et al., 1998: Chap. 7; Lin et al., 1986; Souza et al., 1993). I describe type 1 and type 2 yield stability in terms of regression diagrams, and suggest how they may be associated with different concepts of environmental, economic, and sociocultural sustainability.[24]

Type 1 stability

Type 1 stability (also referred to as static or biological stability), is recognized as the simplest concept of stability. With type 1 stability, the rate of reduction in yield with decreasing environmental mean yield is less for a stable variety than for the population mean. Those with a slope = 1.0 have average stability, with slope increasing above 1.0 decreasing stability, and with slope decreasing below 1.0 increasing stability,

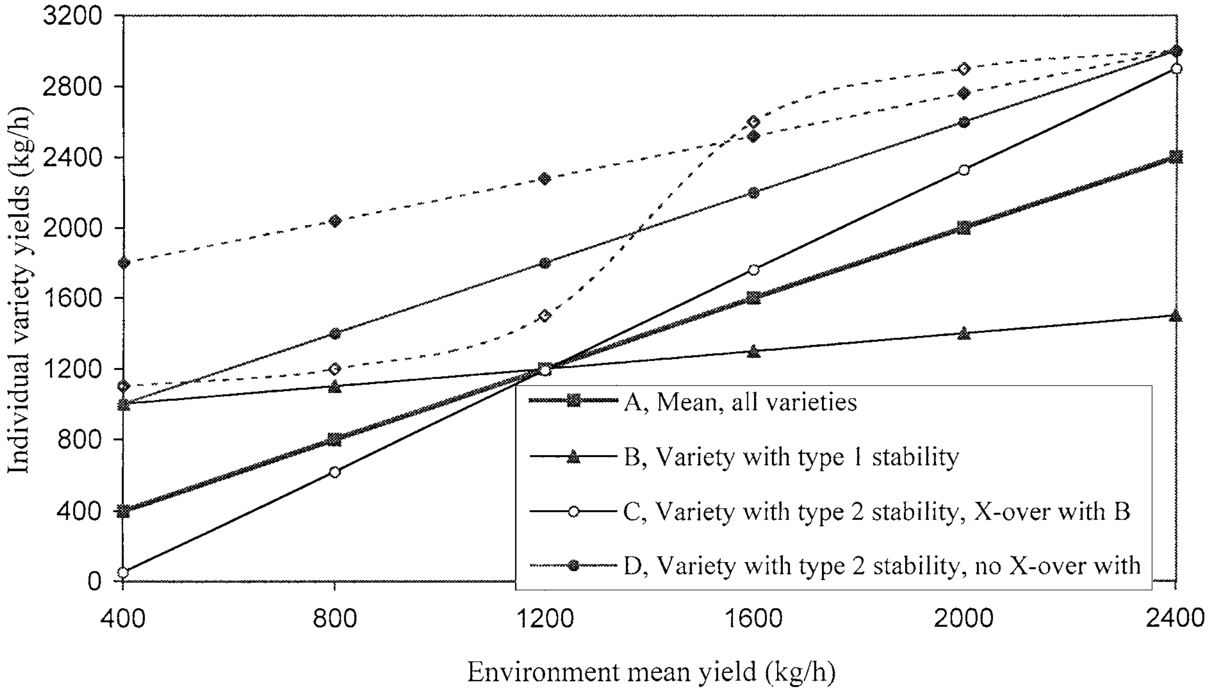

Figure 2. Different types of varietal yield stability in terms of regression slopes.

with a variety having a regression slope = 0 defined as the most stable (variety B, Figure 2).

A goal of type 1 stability implies that plant breeding is driven by supply, dominated by environmental variables, and that an increasingly important goal of plant breeding is responding to the need for maintaining and increasing yields in marginal growing environments. Production is constrained by limits on natural resources for plant production and improvement. An important goal of sustainable agriculture and plant breeding is assumed to be high yield stability in marginal environments, i.e., under stress conditions where resources are limited, and often includes small-scale, Third World farmers (Ceccarelli, 1996b; van Oosterom et al., 1996; Souza et al., 1993).

Type 2 stability

Type 2 stability (also referred to as dynamic or agronomic stability), is preferred by most plant breeders, even though they also recognize the importance of type 1 stability. With type 2 stability, a stable variety is one with a response to environments that is similar to the average of other varieties in the trials under consideration. The most stable variety has slope = 1 (variety D, Figure 2), and varieties with slopes decreasing below 1 or increasing above 1 are increasingly unstable.[25]

A goal of type 2 stability implies that plant breeding is driven by demand, dominated by economic variables, and that the goal of modern agriculture and plant breeding is increasing yield response to improved growing conditions (Eberhart and Russell, 1966; Hildebrand, 1990; Romagosa and Fox, 1993). Economists emphasize the need in defining sustainable agriculture to move away from type 1 stability as a goal, to an economic goal of increasing the slope of total factor productivity, or output (Lynam and Herdt, 1992), in other words, type 2 stability. In this approach, population growth is taken as exogenous, and since sustainable agriculture must feed a growing population, it becomes equal to "sustainable growth" (Lynam and Herdt, 1992). Those who raise questions about the environmental sustainability of modern agriculture and MVs may even be characterized as "anti-scientific" and emotional (Borlaug, 1999). Human scientific ingenuity and technology may be regarded as the only limits to progress. Evans, for example, cites the progressive breaking of barriers to increases in atomic beam energy by successive technological breakthroughs as analogous to progress in increasing crop yield. While a yield plateau is reached for any given input because of diminishing marginal returns, "a succession of new inputs can keep rescuing yield from the plateau" (1993: 29).[26]

A holistic approach to understanding yield stability

Yield stability is an area that is particularly prone to influence by unexamined assumptions, in part because the research necessary to test hypotheses is often complicated and expensive, and data are difficult to analyze and interpret (Tripp, 1995). Plant breeders may recognize that choice and use of these definitions depends on "how the scientist wishes to look at the problem" (Lin et al., 1986: 894), and Evans asserts that the regression diagrams used in the analysis of yield stability have become "the plant breeder's icons, ubiquitous but with a variety of styles to support a variety of dogmas" (1993: 163).[27]

Yet the objectivist approach taken by many plant breeders and others does not explore the relationship between scientific "wishes" and "dogmas" (both aspects of knowledge) and the social and institutional contexts and epistemological processes that engender them. On the other hand, a constructivist approach, taken by most social scientists, generally ignores details of the objective reality of genotypes and environments that is the empirical core of plant breeding science.

In the following section, I take an alternative, holistic approach to understanding plant breeders' choice of selection, test, and target environments in relationship to yield stability. I pose questions, and explore ways of answering them, about how similarities and differences among plant breeders might be accounted for by similarities and differences in their

1) experiences of biophysical reality, that is the germplasm (crop species and varieties) and the selection, test, and target environments they have worked with,
2) experiences of social reality, including social and institutional settings, and
3) to a lesser extent, epistemology as influenced by preexisting knowledge, technology, and practice.

Yield stability and the relationship between selection, test, and target environments

Plant breeding involves four basic steps between deciding on the breeding plan and the release of a new variety: (1) creation of a large amount of genetic diversity through choosing parent germplasm, and by hybridization (crossing), (2) selection of individual plants and populations initially in a limited range of *selection environments*, (3) evaluation of the "best" populations resulting from selection across a wider range of *test environments*, and (4) the choice of varieties for release in the *target environment* on the basis of their potential to out-perform (viz. out-yield) the existing varieties (Stoskopf et al., 1993; Simmonds, 1979).

A fundamental challenge in plant breeding is choosing selection and test environments so that when crop varieties are grown in the target environment (farmers' fields), they will perform as intended, and will out-yield varieties currently being grown there, including FVs. Although it is a commonly accepted maxim that new varieties "of any crop must be tested under the conditions in which they will be grown" (Stoskopf et al., 1993), this is much easier said than done, and the degree to which the selection or test environments, which are relatively quite limited in space and time, can represent 1) the range of locational and management conditions present in the much larger target environment, or 2) the range of temporal variables over the intended lifespan of a new variety, is in fact the subject of much research and discussion in plant breeding.

G×E is at the heart of the problem, because the fundamental question is "How similar will the phenotype (primarily yield) of a given genotype be in the test or target environment, compared to its phenotype in the selection or test environment?" There are three basic ways of dealing with G×E in plant breeding programs: ignore it, avoid it, or exploit it (Cooper and Hammer, 1996c). The choice of selection, test, and target environments includes decisions about the desirable degree of similarity in level of optimality or marginality between them. This includes management practices in the target environment, based on information about the type of farmers there (including the kinds and amounts of inputs they use). Plant breeders differ in their understanding of the stability of varieties in test or target environments as a function of the level of optimality in selection or test environments. In practical terms, this means disagreement over whether breeders should have widely or narrowly adapted varieties as their goal, which can become "at times even emotional" (Romagosa and Fox, 1993). A type 2 definition of yield stability tends to be associated with ignoring or avoiding G×E in developing more *widely adapted* varieties, while a type 1 definition tends to be associated with exploiting G×E in developing more *narrowly adapted* varieties.

A major assumption entailed in choosing a breeding strategy of selection and testing in optimal environments for production in marginal target environments is that there is a lack of qualitative G×E across the range of environments, i.e., high yield in the former will translate into high yield in the latter, referred to by plant breeders as a yield *spillover*. To illustrate, if 2000–2400 kg/h is the selection environment in Figure 2, and 400–800 kg/h the target environment, then variety D has yield spillover from optimal selection environment to marginal target environment, compared with variety B with type 1 stability. However, if there is qualitative G×E for yield between selection and target environments, there will be a change in rank of varieties across environments. In terms of regression analysis, their regression lines crossover, and this phenomenon is commonly referred to by plant breeders as a *crossover*. In Figure 2, if 2000–2400 kg/h is the selection environment, and 400–800 kg/h the target environment, then variety C does not have yield spillover from selection to target environment, and instead has a crossover with variety B (with type 1 stability). In terms of yield stability, the question of whether to choose wide or narrow adaptation as a breeding goal might be stated as whether high yields and high yield stability are compatible breeding goals – type 1 stability implies a "no" answer, and type 2 stability a "yes" answer.

Until recently, relatively little attention has been paid to analyzing the effect of G×E in selection or test environments in relationship to G×E in test or target environments and thus the influence of G×E on yield and yield stability of new crop varieties. An important reason for this is the great complexity of the situation. The advent of powerful new computers, as well as the increasing concern with sustainability and marginal growing environments, has led to a great increase in theoretical and methodological attention by plant breeders to understanding the role of G×E. Especially in the last decade, there has been much progress in the development of sophisticated statistical methods for analyzing the components of G×E, research on the biological basis for G×E, including plant physiology and genetics and the nature of environmental stresses, and the development of practical methods for increasing the efficiency of the selection process in terms of choosing selection, test, and target environments (e.g., Bänziger et al., 1999; Bushamuka and Zobel, 1998; Byrne et al., 1995; Ceccarelli et al., 1998; Cooper et al., 1997; Cooper and Hammer, 1996a; Crossa et al., 1999; Kang and Gauch, 1996; Singh et al., 1999; Vargas et al., 1999).

In the next two subsections I discuss how the choice (implicit or explicit) of type 1 or type 2 yield stability may affect how selection, test, and target environments are defined, in relation to wide adaptation and yield spillovers v. narrow adaptation and yield crossovers.

Wide adaptation and yield spillovers

Use of type 2 stability is often associated with an emphasis on wide or general adaptation to a range of environments, while G×E is ignored or eliminated. Under this scenario yield and yield stability can be positively correlated, and therefore, varieties selected in optimal environments will show a yield spillover to marginal environments. Varieties selected for type 1 stability in marginal environments will always have lower yields in all environments when evaluated along with varieties selected in optimal environments – a crossover will not occur. Therefore, varieties for marginal target environments should be selected in optimal environments.

The wheat breeding program of CIMMYT (International Maize and Wheat Improvement Center, Mexico)[28] is a common example used in support of yield spillovers. This approach uses large numbers of crosses, international testing of advanced lines, and continuous alternating selection cycles in environments that differ but allow expression of high yield (shuttle breeding), which have led to wheat MVs that are widely adapted, are responsive to optimal conditions where they have high yields, and are higher yielding than local varieties in marginal environments (Rajaram et al., 1997; Romagosa and Fox, 1993). Examples of the wide adoption by farmers in marginal target environments of widely adapted wheat varieties developed in more optimal environments supports the existence of spillovers and the success of this method (Braun et al., 1997; Pingali and Rajaram, 1999).

Spillovers are also frequently cited for maize MVs. For example, Duvick states of maize MVs that "it would seem that in most respects selection has preadapted today's hybrids to lower-input agriculture and harsher growing conditions" that may result from the need to make agriculture more environmentally sustainable, or from climate change[29] (1992: 78). A review of maize germplasm selection for low-input (marginal environment) agriculture states that "selection under one set of conditions, … high-input farming, will likely have substantial correlated response under another set of conditions, such as low-input agriculture" (Goodman, 1993: 36).

A review of on-farm trials in five Third World countries comparing maize varieties containing improved CIMMYT germplasm adapted to farmers' environments with FVs, found evidence of crossovers in a minority of cases, and concluded that MVs generally out-yield FVs even in the "worst environments studied" (Pham et al., 1989: 205). In another report of CIMMYT maize breeding research the authors concluded, "These observations suggest that CIMMYT's strategy [of selection in relatively optimal environments] for population improvement and cultivar development has been successful for developing superior maize cultivars for the resource-poor farmers of the developing world, where most of the low-yielding environments occur" (Pandey et al., 1991: 289). In Zimbabwe, maize hybrid MVs have had high adoption rates among limited-resource farmers in more marginal environments (Heisey et al., 1998).

Possible biological explanations for yield and yield stability being positively correlated (i.e., for lack of qualitative G×E) include high genetic correlation between traits expressed in optimal and marginal environments (i.e., the traits are determined by the same genes), and the higher heritability expressed in uniform, optimal environments where environmental variation is minimized, thus optimizing the genetic changes achievable by plant breeders (Rajaram et al., 1997; Romagosa and Fox, 1993).

Narrow adaptation and yield crossovers

Use of type 1 stability is often associated with an emphasis on narrow or specific adaptation, often to marginal environments, and on the exploitation of G×E. Under this scenario, yield and yield stability can be negatively correlated, so that varieties selected for type 2 stability in optimal environments will have lower yields in marginal environments than varieties selected in marginal environments. In terms of regression analysis, varieties selected in optimal environments in relation to other varieties will show a yield crossover from optimal to marginal environments – a spillover will not occur. Therefore, varieties for marginal target environments should be selected in those environments.

According to some observers, an emphasis on wide adaptability in breeding MVs has meant that breeders have not exploited G×E to breed crops with higher average yields for marginal environments (Simmonds, 1991; Ceccarelli et al., 1994). Simmonds' widely cited article based on simulations suggests that because Green Revolution MVs developed at the CGIAR Centers have targeted relatively optimal environments (with high-input farmers), that "selection has inevitably, but unconsciously" been for high yielding, high response varieties (those with type 1 stability), and that for high performance in marginal target environments, selection must take place in those environments (Simmonds, 1991: 367). Thus, positive correlations between regression slopes and yield are a normal finding for MVs because test environments where they are measured are optimal (variety C in environments with mean yield >1200, Figure 1), whereas a negative correlation would be expected in marginal environments (variety C in environments with mean yield <1200, Figure 1). Therefore, there may be crossovers between MVs with relatively steep regression slopes (like variety C), and varieties with type 1 stability (variety B) such as some FVs, when evaluated across a wide range of optimal and marginal target environments.

A focus on narrow adaptation assumes that selection and testing for a given target environment needs to be done in environments that have the same or very similar conditions as those in the target environment, with the possible result that there will be different varieties specifically adapted to these environments, in other words the likelihood that the target environment as originally defined under the assumption of wide adaptation, should be divided into more than one smaller target environment (Podlich et al., 1999). This means exploiting G×E, rather than ignoring or eliminating it, through selecting crop varieties for resistance to the specific stresses that characterize those environments (Bramel-Cox, 1996; Ceccarelli et al., 1998).

Crossovers in performance between varieties are "common" and reflect differential adaptation to different environments (Evans, 1993: 165ff.). This is sometimes the case when MVs and FVs are compared – MVs out-yield FVs under optimal conditions, while FVs out-yield MVs in marginal environments such as those of many Third World farmers (e.g., Kelley et al., 1996 for pearl millet; Ceccarelli et al., 1994 for barley and lentil). Evidence from studies with barley (Ceccarelli, 1996a) indicate that only severe stress comparable to farmers' fields in the region, reveals superior genotypes for such conditions, not evident at intermediate levels of drought stress nor under non-stress conditions.

Crossovers are also frequently cited for maize. Improvement of maize for marginal (drought and nitrogen stressed) environments – especially those with yield reductions greater than 40% – suggests that in both cases selection in the marginal target environments, or careful simulations of specific stresses in those environments, is significantly more effective for improving yields than selection in optimal environments (Bänziger and Lafitte, 1997; Bolaños and Edmeades, 1996).

Possible biological explanations for yield and yield stability being negatively correlated (i.e., for qualitative G×E) include low genetic correlation between traits expressed in optimal and marginal environments (i.e., the traits are determined by different genes), reduction in individual and populational buffering of MVs because of reduction in genetic diversity, and biophysical limits to simultaneously increasing yield and decreasing yield stability (Bramel-Cox, 1996; Ceccarelli et al., 1994; Simmonds, 1991).

A holistic analysis

A holistic analysis of the disagreement over wide vs. narrow adaptation in plant breeding suggests that variables in both the biophysical and social environment may affect epistemology and knowledge of plant breeders.

Biophysical reality

Discussions of the significance of what is often contradictory evidence regarding selection and test environments for marginal target environments suggests that a major source of the differences may lie in the range of environments being considered (Ceccarelli, 1996a). Ceccarelli et al. (1998) criticize Rajaram et al.'s (1997) claim that selection in optimal environments results in wheat varieties that are adapted to marginal environments, because they do not include a broad enough range of environments in their trials. The claim for increasing yield stability of maize MVs cited above (Duvick, 1992: 78) is based on the lack of qualitative G×E, yet the significant and steady increase through time in the regression slope for hybrids released in the decades from the 1930s (0.41) to the 1980s (1.51), and the high mean yield of the lowest environment (5000 kg/ha, compared with an average yield of 2260 kg/ha in developing countries in 1989 (Evans, 1993: 281)) suggest the probability of qualitative G×E when examined across a wider range of environments. Thus, Duvick's statement that maize hybrid MVs are preadapted to sustainable agriculture is based on assumptions about the kinds of range of stress for which adaptation will be necessary.

Different conclusions about adaptation are reached in four recent articles, all by CIMMYT scientists, reporting evaluation of maize genotypes selected in different types of environments across a range of test environments. Two conclude that selection in optimal environments produce genotypes with higher yields than locally adapted genotypes in marginal target environments (Ceballos et al., 1998; Pandey et al., 1991). The other two conclude that selection should take place in marginal environments that have similar stresses to the target environments (Bänziger et al., 1997; Edmeades et al., 1999). The two former studies are based on a narrower range of environments 0.5–3.6 and 4.3–6.5 tons/hectare) than the later (0.7–7.8 and 1.0–10.4).[30]

Social reality

There is also evidence to support the idea that the choice of selection, test, and target environments is influenced by social reality, and by preexisting knowledge, including values. Advocates of both type 1 and type 2 stability have used the term "traditional" pejoratively to describe the contrasting approach, implying that their own is the more scientific and innovative. For example, in support of specific adaptation, Cooper and Hammer state that "Traditional selection strategies often have focused on improving broad adaptation" (1996c: 597), and Simmonds that "traditionally, most plant breeding takes place ... on the experiment station" (1991: 366). In support of wide adaptation, Rajaram et al. state that "The traditional methodology, which has been practiced for many years in varying forms, is typified by handling of all segregating populations under target conditions of drought, and recommends the use of local landraces in the breeding process" (1997: 163).

Values are also reflected in assumptions made by plant breeders about target environments, including sociocultural and economic factors affecting farmers' management. The goals of type 2 yield stability and wide adaptation are often associated with the assumption that the most appropriate target environment is one where farmers have full access to the range of modern inputs, and plant breeders often "project their cultivar objectives to anticipated use by the better growers, and it is logical that better growers are attracted to better environments" (Jensen, 1988: 411). Alternatively, farmers should modernize in order to make their farming systems appropriate for production of the MVs that plant breeders produce. For example, "Since improved varieties are usually better able to take advantage of this extra investment, they can thus be regarded as an incentive for farmers to raise their level of inputs and to improve their management of maize" (Pham et al., 1989: 205). If target environments are so marginal that yield spillovers do not occur, then it may be assumed that it is not appropriate to develop MVs for these environments – they will have to be improved before high yielding MVs can be adopted there, since experience suggests that "improvements in crop and resource management technologies ... often precede changes in variety," or these marginal environments should be taken out of crop production (Pingali and Rajaram, 1999: 16).

In terms of farmers' reasons for not adopting MVs, a type 2 yield stability approach emphasizes lack of economic incentives rather than institutional or physical barriers. This implies breeding for profit-maximizing farmers who invest in production close to the level where the marginal value of their production equals the marginal cost, i.e., a gamble that, on average, good years will balance bad years, and that they will have the resources to survive the occasional disastrous yield (see Barah et al., 1981; Ellis, 1993). There may also be the assumption that there are cultural barriers, for example that farmers are "only dimly aware of the potential benefits of improved germplasm and crop management practices," and lacking the education and skills needed to manage MVs "properly" (Aquino, 1998: 249).

In the approach of type 1 yield stability and narrow adaptation, programs at the CGIAR International Agricultural Research Centers (IARCs) and the National Agricultural Research Services (NARS) are criticized because they have tended to focus on the "progressive farmer" in relatively optimal environments (Ceccarelli et al., 1994; see also Evans, 1993), thus ignoring poorer farmers. This alternative suggests that reducing poverty via technical change is difficult, and that yields in marginal environments will, however, have to increase, since achievable yield increases in more optimal environments alone will not be adequate (Heisey and Edmeades, 1999). For example, "Maize yields in farmers' fields in many tropical countries ... [are] in stark contrast to yields ... reported on breeding stations in those same countries. ... Farmers' fields are rarely characterized by only one abiotic stress. ... Resource constrained farmers in many parts of the tropics may apply no fertilizer at all (Bänziger et al., 1999: 1035). Therefore, plant breeders should adapt their breeding goals to meet the needs of farmers' in these marginal environments.

The use of type 1 stability may assume that farmers favor varieties with relatively low mean yield but higher yield stability. That is, farmers invest in production at levels where their marginal cost is significantly less than the marginal value of their production, thus forgoing potential profit in favor of security (Ellis, 1993; Walker and Jodha, 1986). This may be because the farmer is risk averse, valuing greater certainty (stability) more than a higher average yield, or because she adopts a "safety first principle" to avoid disaster, opting for a minimum food supply in all but the worst years (Smale et al., 1995). While a well-off farmer would have the resources to survive the worst years, and benefit from the higher mean yield averaged over all years, many poor farmers may not have the resources to do so (Simmonds, 1988). Under standard economic analysis favored by type 2 stability, this degree of stability is not a desirable criterion for allocating resources, because "the optimal level of resource use is not being followed and profit is not maximized" (Ellis, 1993: 90).

This analysis suggests that plant breeders supporting either spillovers or crossovers to target environments from selection in optimal selection environments, have generally not paid enough attention to understanding and testing the assumptions on which their generalizations are based. Because of this, they may be drawing general theoretical conclusions at a level different than those that are justified by their data. Explicit examination of the whole plant breeding system (Figure 1) should help identify important variables that have not been adequately investigated.

Conclusion

Our ability to develop more sustainable agriculture will depend to an important degree on a clearer understanding of the joint contribution of biophysical and social reality to scientific knowledge, and of the epistemological processes of its production. Such an understanding will be necessary for us to judge the usefulness of scientific knowledge as the basis of agricultural policy and practice. Plant breeding is a key component of agriculture, and the relationship between yield and yield stability is one of the most fundamental and complex concepts in plant breeding – an important factor in determining the response of plant breeding to the challenge of making agriculture more sustainable.

Current approaches to understanding scientific knowledge, including that of plant breeding, tend to be dominated by objectivist and constructivist approaches, each of which fails to consider important components of its production. In this article I have proposed a holistic approach that considers both the possibility that plant breeding science is an objective reflection of biophysical reality, *and* is socially constructed via technology, practice, and preexisting knowledge as influenced by the institutional, social, and political contexts in which it takes place (Figure 1).

I have used this approach for exploring the causes for differences among plant breeders for the case of yield stability. A review of the general literature along with some key examples suggests the following answers to the questions posed in the Introduction: 1) the working definition of yield stability emphasized by individual plant breeders may differ, in part as a result of their assumptions about agricultural sustainability; 2) differences among plant breeders in their knowledge and practice regarding selection, test, and target environments can be accounted for in part by differences in the definition of yield stability they use; 3) the choice of selection, test, and target environments and of genetic diversity may affect the sustainability of agriculture; and 4) plant breeders' understanding of yield stability in relationship to wide v. narrow adaptation and the choice of selection, test, and target environments, can be explained as the result of both similarities and differences in biophysical and social reality on which knowledge is based, and in the epistemological process of its production.

Thus, my preliminary answer to the question posed in the title of this article is "both" – plant breeding science, like all other science, is a mixture of objective truth (an uneven process of increasing accuracy in understanding objective reality) and social construction (understanding of objective reality dominated by external social forces).

However, the analysis presented here is only preliminary, and is meant to suggest more specific hypotheses, which will need to be tested through detailed empirical research. The results could increase the probability of finding a balance in plant breeding programs between yield and yield stability, i.e., between the use of type 1 and type 2 yield stability, between local adaptation and broad adaptation, and between crossovers and spillovers. The process of finding this balance will contribute to defining and achieving more environmentally, socially, and economically sustainable agriculture. It will also contribute to understanding the potential contribution to sustainability of three major new challenges for plant breeding for the 21st century – the integration of *in situ* and *ex situ* conservation of crop genetic diversity, the possibility of collaboration between plant breeders and farmers in crop improvement, and the use of the new biotechnologies for exploring and manipulating the genetic basis of crop phenotypes.

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Notes

1. The Green Revolution brought MVs and higher-input agriculture to the Third World. Simmonds succinctly defines it in biological terms as a process that "exploited semidwarf cereal varieties grown under good water control and with high chemical inputs; in short, a 'package' that exploited a strong positive" G×E (Simmonds, 1990: 340).
2. Plant breeders use the term "environment" to mean a crop growing environment, composed of a spatial location (e.g., a region, a field, a location within a field), a year (or season within a year); it sometimes includes the management regime (e.g., different applications of nutrients or water). Throughout this article I use the term "marginal environments" in a general way to refer to crop growing environments that have relatively high levels of stress for yield production (e.g., drought), that often have relatively high levels of variability in these stress factors through space and time (e.g., rainfall with high spatial, intraannual, and interanual variation), and where farmers do not apply many external inputs (e.g., irrigation water). In contrast, I use the term "optimal environments" to refer to crop growing environments that have relatively low levels of stress for yield production, that usually have relatively low levels of variability through space and time, and where farmers apply relatively high levels of external inputs. Marginal and optimal are terms commonly used in the plant breeding literature, although often without clear definitions. I refer to a particular locational, spatial, or management component of marginal or optimal environments when relevant to the discussion.
3. See note 2.
4. "Genotype" is the genetic composition of an organism, and is commonly used to refer to the genetic make-up of an individual plant or a population.
5. Genetic diversity is a measure of the number and evenness of distribution of alleles at the individual and population levels, and is also referred to as genetic variance. An allele is an alternative form of a gene; a gene is the basic unit of hereditary information coded in the DNA of chromosomes; chromosomes in most higher plants and animals (i.e., diploid) come in homologous pairs, so each individual can have two different (or similar) alleles, and in a population a gene may have many different alleles.
6. An important part of these contexts, especially perhaps in marginal environments, is farmers' knowledge, although this is not explored in this article. An understanding of the reasons for similarities and differences between farmers' and plant breeders' knowledges may help to understand adjustments necessary in plant breeding theory and practice for marginal environments (Cleveland et al., 2000; Soleri and Cleveland, 2001).
7. Debates about sustainable agriculture are often obfuscated by generalizations at too superficial a level, often due to an individual's unexamined assumptions based on their values and the unique contingencies of their experience (see Thompson, 1995). The situation within plant breeding and the closely related area of crop genetic resource conservation appears to be no different (as described for example by Tripp, 1996).
8. I use the terms "objectivist" and "constructivist" as convenient labels for two different broad categories of approaches to understanding scientific knowledge, with the caveat that that there are many differences in individual approaches. Harding suggests that "co-constructionist" is a more appropriate term than "constructionist," because nature is usually considered in these approaches to have an effect on its social representation, and because social representation of nature is affected by other elements of society (Harding, 1998). In social studies of science the terms "internalist" and "externalist" are sometimes used as synonyms for "objectivist" and "constructivist" respectively (as do e.g., Harding, 1998; Hull, 1988).
9. Epistemology is a popular topic these days in science studies and in social sciences and humanities in general, but the term is often not clearly defined. In philosophy, epistemology is sometimes defined more broadly to include

processes of justification of knowledge (Alcoff, 1998; Audi, 1998). Some would even abandon the concept altogether as a creation of Western positivism in favor of, for example, hermeneutics (Rabinow, 1996).

10. I have not included discussion of human biology, or of individual differences in this article.
11. Allard's revision of his widely used and respected introductory plant breeding textbook is explicitly based on a framework of Darwinian and Mendelian evolutionary principles, and the first chapter is titled "Darwinian Evolution" (Allard, 1999). Darwin on the other hand realized the importance of studying the work of contemporary plant and animal breeders, and his documentation of "variation under domestication" was important in the development of his idea of natural selection (Allard, 1999: 9).
12. For example, the demonstration by Johannsen that quantitative traits followed the same principles of inheritance that Mendel demonstrated for qualitative traits, by Nilsson-Ehle and by East that many different genes could effect one character, by Turesson that different genotypes of a species are adapted to a specific range of environmental variables, and by Fisher and associates that the inheritance of quantitative characters could be analyzed statistically (Allard, 1999; Hill et al., 1998).
13. One prominent plant breeder has stated that, "Modern methods of statistical design and analysis add precision to all of these decisions and quantitative genetic theory adds rationality to breeding plans, but art and experience – not precision genetics – are the key to successful use of these useful tools" (Duvick, 1996: 543).
14. One of the most extensive surveys of plant breeding in the United States found that there has been a loss of time spent on plant breeding in the public sector and an increase in the private sector, and that the public sector spends much more effort on basic research, and much less on developing new varieties, than the private sector (Frey, 1996). It attributes the movement of plant breeding toward the private sector to legal (intellectual property protection) and scientific (biotechnology) innovations that make plant breeding more profitable. There are also major disagreements between plant breeders about how intellectual property rights should be used in plant breeding (Cleveland and Murray, 1997).
15. A recent review by a plant breeder comparing selection progress in development of maize hybrids compared with OPVs states that the data suggest "the unsettling conclusion" that an OPV approach has been more effective in increasing yield than hybrid breeding, but that this comparison is "unreasonable" because of differences between the two systems (Coors, 1999).
16. Kloppenburg reports that in 1920 when Henry C. Wallace was appointed secretary of agriculture, he in turn appointed an advocate of hybrids to be in charge of maize research (1988). Henry's son founded Pioneer Hi-bred International, which became the world's largest producer of hybrid maize seed.
17. The CGIAR is the Consultative Group on International Agricultural Research, which includes over 40 donors, dominated by the industrial countries, and 16 International Agricultural Research Centers (IARCs). It is the most prestigious group of its kind, and is considered to be the originator and primary proponent of the Green Revolution approach to agricultural development.
18. The term "holistic" is not entirely satisfactory, but seems preferable to others for the time being. Hull proposes the term "naturalistic" for this approach (Hull, 1988: 3).
19. This parallels work of some social scientists who are advocating a movement toward more inductive, eclectic approaches that seek a middle ground between objectivist and constructivist poles (Bernard, 1998; Ellen, 1996; Schweizer, 1998).
20. See note 25.
21. The "*phenotype*" is the sum of an organism's physical properties, the outcome of the interaction between genotype and environment. The basic relationship is described by the following equations: $P = G + E + G{\times}E$ (where P = yield phenotype, measured for example in kg per hectare of grain harvested, G = genotype, and E = environment); and $V = V_G + V_E + V_{G\times E}$ (where V = yield variance, i.e., yield stability, V_G = genotypic variance, V_E = environmental variance, and $V_{G\times E}$ = variance due to G×E).
22. A number of other measures of stability are also used by plant breeders (Hill et al., 1998; Souza et al., 1993; Yan and Hunt, 1998). The simplest is deviation of a genotype from the average of all genotypes, i.e., variance (s^2) across environments defined by average yield, and *coefficient of variation* ($CV = s/\bar{X}$) (see note 25).
23. See note 2.
24. Sustainability as a general concept is often defined in terms of three major components, environmental, economic, and sociocultural (e.g., see Goodland, 1995), and these are often used for sustainable agriculture, as well, for example defined as agriculture that conserves resources for future generations, is economically viable, and promotes social equity (cf. Francis and Callaway, 1993; Thompson, 1995).
25. Type 1 and 2 stability can also be defined in terms of s^2 and CV (see note 22); (Lin et al., 1986). This method is the one most frequently used in aggregate stability analyses, typically by economists, who disagree about whether s^2 or CV is a better measure of stability, a debate that is analogous to the one in plant breeding over the use of type 1or type 2 stability. Even when absolute stability (s^2) increases with increases in yield, relative stability (CV) will remain the same or decrease if increases in average yield are large enough. Thus, a choice between these two measures can be seen as a choice of whether to emphasize yield stability or yield. Anderson and Hazell suggest that even when yield increases are great enough that the CV does not increase as s^2 increases, the risks for poorer households can still increase (Anderson and Hazell, 1989b: 347; see also Lipton and Longhurst, 1989).
26. "Ideal" crop varieties have also been proposed. They have a slope similar to that of varieties with type 1 stability, but with very high mean yields across optimal *and* marginal environments (Variety E, Figure 2) (Duvick, 1992; Finlay and Wilkinson, 1963: 752; see also Byerlee, 1996). Thus, proposing them as a plant breeding goal makes the same assumption as proposing type 2 yield stability – no necessary negative correlation between yield and yield stability across the range of target environments. Ideal varieties

have also been defined as those with non-linear regression slopes, with low G×E in marginal environments, and high G×E in optimal environments (Variety F, Figure 2) (Federer and Scully, 1993). Ideal varieties are sometimes presented in plant breeding textbooks as an accepted practical goal. For example, "simultaneous yield and sensitivity selection" may be "desirable to achieve yield stability" (Stoskopf et al., 1993: 112), and ideal varieties are implied in defining yield stability as "the ability of the plant genotype to produce up to its genetic potential in spite of an adverse environment" (Poehlman and Sleper, 1995: 217).

27. Thus it may be that it is not so much that there is unacknowledged use of different models by supporters and opponents of MVs as Tripp suggests (1996), especially among plant breeders, but that the possibility of differences in socially constructed knowledge underlying the choice of model is unrecognized.
28. CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo) is the descendent of the first Mexican Agriculture Program, which began in the 1940s, and is recognized as the beginning of the Green Revolution and of the CGIAR (see note 17) (Jennings, 1988; Stakman et al., 1967).
29. Duvick does, however, see the possibility for poor performance of maize MV hybrids if the more marginal conditions entail reduced herbicide use and lower planting densities, because the hybrids' upright leaves would allow increased sunlight to reach the ground, causing increased weed growth and evaporation.
30. As more sophisticated technologies in the form of genetic, molecular, and statistical analysis are applied to understanding G×E affecting yield stability, the role of specific differences between particular genotypes and environments is becoming clearer, while the overall situation appears more complex, further increasing understanding of the danger of making generalizations at too superficial a level. For example, CIMMYT maize researchers are now suggesting that while there are not spillovers from selection in optimal to performance in marginal (drought or nitrogen stress) environments, that there are spillovers in the other direction (Bänziger et al., 1999; Edmeades et al., 1999), so that widely adapted maize varieties should be possible, although assuming that they are developed in a very different way than had been previously. In comparison with the situation for barley, they suggest that this result may in part be due to the unique nature of maize biology, and the fact that unlike barley, maize is grown fairly frequently in optimal environments (Chapman et al., 1997).

The ability to identify and move genes associated with specific traits between distantly related organisms may also lead to a novel empirical situation that will require rethinking the relationship between yield and yield stability. One relevant example is research on maize lines showing them to be statistically associated with specific adaptation to highland or lowland environments, and molecular analysis demonstrating that these lines have distinctive sets of linked genetic markers (Crossa et al., 1999). The researchers suggest that genetic engineering to move lowland alleles into highland germplasm could result in broader adaptation of highland maize, without loss of its specific adaptation to highland environments, assuming that these are truly separate sets of loci.

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