Quantitative population epigenetics - a catalyst for sustainable agriculture

Quantitative Populations-Epigenetik, Katalysator für eine nachhaltige Landwirtschaft

Reinhold Stauß

Ritzebeker Weg 13, 24222 Schwentinental district Klausdorf, Germany
Reinhold.Stauss@web.de

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Abstract

The use of quantitative population epigenetics and the related importance of stress can lead to a paradigm shift, away from a high-input and high-output agriculture with a maximum utilization of the genetic potential to an ecological intensification, to a low-input and high-output agriculture which is optimization and harmonization of limiting stress factors to achieve maximum results with limited environmental or ecological resources.

Keywords: Agricultural ethics, ecological intensification of agricultural practices, high-output, low-input, quantitative population epigenetics, stress

Zusammenfassung

Die Anwendung der quantitativen Populations-Epigenetik und die damit verbundene Bedeutung von Stress kann einen Paradigmenwechsel unterstützen, weg von einer „High-Input, High-Output"-Landwirtschaft mit einer maximalen Ausnutzung des genetischen Potentials hin zu einer ökologischen Intensivierung, zu einer Optimierung und Harmonisierung von begrenzenden Stressfaktoren, zu einer „Low-Input, High-Output"-Landwirtschaft, mit einer maximalen Nutzung des Umweltpotentiales.

Stichwörter: Agrarethik, High-Output, Kulturelle Nachhaltigkeit, Low-Input, ökologische Intensivierung der Landwirtschaft, quantitative Populations-Epigenetik, Stress

Introduction

Quantitative population genetics describes the variability observed in characters due to genetic variation. Quantitative population epigenetics describes the variability observed in characters due to factors in the environment -- induced primarily by factors of the agricultural system (STAUSS, 1992; STAUSS, 2012).

The “breeder” improves the genotype - for him environments are "fixed” effects. The farmer strives to intervene in the environment by effecting a specific phenotypic expression, within the norm of reaction inherent in the genotype.

The application of quantitative population epigenetics as a catalyst for sustainable agriculture offers earning opportunities (market segments or business cases) for the existing players in the high-input agriculture in terms of win-win.

For example, agriculture is a major factor in eutrophication of surface waters. By using epigenetically active compounds to switch on yield or stress genes, new crop varieties for low-input agriculture could be developed to improve nitrogen and water use efficiency for cereal production significantly.

Background and objectives

One of the early goals in quantitative genetics was to quantify levels of heritable variation in order to distinguish how much of the standing variation in populations was due to genetic or environmental causes (LYNCH and WALSH, 1998). For this purpose, evolutionary genetics has focused on a measure first introduced in animal breeding: heritability (h^2). For environmental causes “one minus heritability ($1 - h^2$)” is a measure of the portion of variability that is due to environmental effects (STAUSS, 1992; STAUSS, 2012).

An essential requirement to determine an environmental potential for a low-input and high-output agriculture is to quantify the amount of environmental variability expressed for traits under consideration. CHARMANTIER and GARANT (2005) showed in a review article, that the magnitude of the genetic and environmental components of phenotypic variation can change with environmental conditions. Results provide evidence for decreased heritability in more stressful and unfavourable conditions, significantly so for morphometric traits but not for traits more closely related to fitness, which have per se lower values. In addition, in stressful conditions such as food shortage, resource allocation to various physiological functions may favour traits that directly affect survival to the detriment of less vital functions such as morphological characters. Hence, this could explain that heritability of morphometric traits tends to decrease more in unfavourable growth conditions than heritability of traits more closely related to fitness.

Environments with high-yield potential and high heritability enable maximum use of the genetic yield potential (BRAUN, 1984; PFEIFFER, 1984) - often resulting in high-input agricultural production systems with an overuse of groundwater, natural resources and biodiversity.

Ecological intensification of agricultural practices can be a low-input and high-output agriculture. The use of quantitative population epigenetics and the related importance of stress (STEINBERG, 2011) can support such intensification. There can be a paradigm shift, away from a maximum input system with a maximum utilization of the genetic potential (maximization of h^2) towards a minimum input system with a maximum utilization of the epigenetic potential, that is, to an optimization of limiting stress factors (maximization of $1-h^2$) to achieve maximum results with limited environmental or ecological resources:

- low-input with high-output and
- utilization of the genetic potential (inherited characteristics) and the environmental potential or environmental inheritance (acquired characteristics).

For the agricultural and the food industry there is a need for an ecological intensification of agricultural practices (LÖWENSTEIN, 2011) there is a need for a second green revolution. This second green revolution, however, can only be done on the basis of an agricultural ethics that takes into account the ecological, social and cultural sustainability (MEIER, 2012).

Results and work packages

Ecological intensification of agricultural practices offers earning opportunities (market segments or business cases) for the existing players in the high-input agriculture in terms of win-win, especially in utilization of genotype-environment interactions.

<u>Work package Lessons to learn from breeders</u>

Likewise in breeding, index selection can be appropriated to improve efficiency in screening environmental factors as for example biologically active chemical compounds, soil preparation techniques, etc., for potential to enhance quantitative characters, such as yield, standability and resistance to unfavourable environmental influences.

Breeder and chemical researcher are different sides of the same coin (organism). The breeder improves the genotype - for him environments are "fixed” effects. The “environmental” researcher strives to intervene in the environment by effecting a specific phenotypic expression by modifying the environment, within the "norm of reaction" inherent in the genotype.

Likewise basic rules for experimental designs and data analysis appropriated by breeders can be applied

- experimental designs: fix or random effects, size, trial conditions e.g. stress or non-stress, etc.
- post-experimental evaluations,
- optimization of experimental designs and
- quantitative description of single or multiple traits designs e.g. using selection indices.

A comparison of quantitative population genetics with quantitative population epigenetics (Tab. 1) makes this obvious.

Tab. 1 Comparison of quantitative population genetics with quantitative population epigenetics.

Tab. 1 *Vergleich von quantitativer Populations-Genetik mit quantitativer Populations-Epigenetik.*

Quantitative population genetics	**Quantitative population epigenetics**
Quantitative genetics is the study of continuous traits (such as height or weight) and their underlying mechanisms. It is effectively an extension of simple Mendelian inheritance in that the combined effect of the many underlying genes results in a continuous distribution of phenotypic values (WIKIPEDIA CONTRIBUTORS. Quantitative genetics[Internet]).	Quantitative epigenetics is the study of continuous traits (such as height or weight) and their underlying mechanisms. It is the combined effect of the many underlying genes and epigenetical effects resulting in a continuous distribution of phenotypic values.
The main application of quantitative genetics to artificial and natural populations has been to use the pattern of genetic variances and covariances to predict the response of the mean phenotype to selection (BARTON, 1990).	The main application of quantitative epigenetics to artificial and natural populations could be to use the pattern of genetic variances and covariances to predict the response of the mean phenotype to regulator-active factors of the farming system or to biologically active chemical compounds as artificial environmental factors.
From genome to phenotype (inherited characteristics): Quantitative genetics aims to link phenotypic variation for complex traits to its underlying genetic basis in order to better understand and predict genetic architecture and long term change within natural, agricultural, and human populations. Traditionally built upon statistical abstractions of genetic effects, the field is now rapidly advancing by making use of recent exciting developments in genetic and genomic technologies to reveal explicit links between genes and complex phenotypes, and therefore serves as a focal point for bringing together many emerging areas of genetics, genomics, physiology, statistics, bioinformatics, and computational biology. This synthesis is already having a large impact on the areas of evolutionary biology, plant and animal breeding, and the genetic analysis of human disease.	From "environment" to phenotype (acquired characteristics): Quantitative epigenetics aims to link phenotypic variation for complex traits to its underlying epigenetic basis in order to better understand and predict epigenetic architecture and changes within natural, agricultural, and human populations – due to environmental factors. Traditionally built upon statistical abstractions of epigenetic effects (environmental, biologically active chemical compounds), the field could be used to reveal explicit links between epigenome and complex phenotypes, and could therefore serves as a focal point for bringing together many emerging areas of genetics, epigenetics, genomics, physiology, statistics, bioinformatics, and computational biology. This synthesis could have a large impact on the areas of evolutionary biology, selection and development of factors of the agricultural system or biologically active chemical compounds, and the epigenetic analysis of human disease.

The results of breeding trials in recent years and decades with their estimates of variance components can be used in epigenetic approaches analogously. Single nucleotide polymorphism (SNP) epigenotype analysis of biologically active factors of the farming system with SNP-Chips could be used to reveal explicit links between epigenome and complex phenotypes.

<u>Work package win-win for actors in "Food production"</u>

In the proposal for a regulation of the European Parlament and Council establishing Horizon 2020 - the Framework Programme for Research and Innovation 2014-2020 (EUROPEAN COMMISSION, 2011) the European Commission formulates under Section 2. "Food Security, Sustainable Agriculture, Marine and Maritime Research and the Bioeconomy" page 62 the Specific Objective 2.1 "The specific objective is to secure sufficient supplies of safe and high quality food and other bio-based products, by developing productive and resource-efficient primary production systems, fostering related ecosystem services, alongside competitive and low carbon supply chains. This will accelerate the transition to a sustainable European bio-economy". And then explains "In essence, a transition is needed towards an optimal and renewable use of biological resources and towards sustainable primary production and processing systems that can produce more food and other bio-based products with minimised inputs, environmental impact and greenhouse gas emissions, enhanced ecosystem services, zero-waste and adequate societal value. A critical effort of interconnected research and innovation is a key element for this to happen, in Europe and beyond."

Such a transition, with quantitative population epigenetics as a catalyst, should steer the entire economy to a paradigm shift toward sustainable economic regimes, away from maximum input systems towards low-input systems with high-outputs, that is, to an optimization of limiting factors to achieve maximum results with limited environmental resources.

Examples for sustainable agriculture:

- Nutritional deficiencies and for example use of a genotype-low-nitrogen interaction (low-input/high-output-varieties, breeding companies).

  The breeding programs should be based on the philosophy of releasing "low-input" varieties in response to the decreasing availability of resources, the need to protect the environment and the likelihood of unfavourable changes in climate. This approach involves breeding plants that have reduced requirements for water, fertilizer and pesticides, and where possible, simpler cultural requirements. Biodiversity protection is also important and promising new lines should be carefully assessed before release to ensure that they do not have weedy tendencies.

  A new variety using a genotype-low-nitrogen interaction is an earning opportunity solving eutrophication problems and is a high yielding variety on marginal soils.

- Bioactive "additives" (regulator-active compounds) to switch on yield genes of nitrogen deficiency or to switch on quality genes (chemical industry, fertilizer industry).
  - nutrient availability

  Roots provide plants with water, minerals, and anchorage (LLORET, 2002). In order to adapt to a very heterogeneous environment, root architecture is extremely plastic, responding to nutrient concentrations in the soil (LÓPEZ-BUCIO *et al.*, 2003), soil matrix heterogeneity (HINSINGER *et al.*, 2005; HODGE, 2006) and biotic interactions (OSMONT *et al.*, 2007; PÉRET *et al.*, 2009).

  The ability of plants to respond appropriately to nutrient availability is of fundamental importance for their adaptation to the environment. The responses of root architecture to nutrients can be modified by plant growth regulators, such as auxins, cytokinins and ethylene, suggesting that the nutritional control of root development may be mediated by changes in hormone synthesis, transport or sensitivity. Recent information points to the existence of nutrient-specific signal transduction pathways that interpret the external and internal concentrations of nutrients to modify root development (LÓPEZ-BUCIO *et al.*, 2003).

  Although root system architecture (RSA) is a highly plastic trait and varies both between and among species, the basic root system morphology and its plasticity are controlled by inherent genetic factors. These mediate the modification of RSA, mostly at the level of root branching, in response to a suite of biotic and abiotic factors. Recent progress in the understanding of the molecular basis of these responses suggests that they largely feed through hormone homeostasis and signalling pathways. Novel factors implicated in the regulation of RSA in response to the myriad endogenous and exogenous signals are also increasingly isolated through alternative approaches such as quantitative trait locus analysis (OSMONT *et al.*, 2007).

  Few root traits have so far been used successfully in plant breeding for enhanced P and Zn uptake in rice or any other crop. Insufficient genotypic variation for traits or the failure to enhance nutrient uptake under realistic field conditions are likely reasons for the limited success (ROSE *et al.*, 2012). One potential complication of conventional breeding for improved nutrient acquisition is that nutrient deficiencies tend to be patchy across field plots. Heterogeneous nutrient availability at screening sites can result in environmental effects masking genetic effects and, as a result, the realized heritability may be rather low (ROSE *et al.*, 2012).

– quality of food

Tomato fruits from organic farming accumulate more nutritional compounds, such as phenolics and vitamin C as a consequence of the stressing conditions associated with farming system (OLIVEIRA *et al.*, 2013).

– quality of plant ingredients, quality of bioactive compounds in plants

Studies have shown that diterpenecarnosic acid plays a role as an antioxidant in rosemary, a drought-tolerant species. This mechanism were also measured in a drought-recovery cycle in leaves of sage (*Salvia officinalis* L. *subs. officinalis*), a drought-susceptible species, growing in Mediterranean field conditions. Results suggest that the same mechanism of antioxidative protection by carnosic acid applies in rosemary and sage, and shows that it is the complete set of antioxidants (and not a single mechanism) that is responsible for avoiding drought-induced damage in plants (MUNNÉ-BOSCH *et al.*, 2001).

Many of the antioxidants are produced by plants in response to oxidative stress. If the plant experiences stress (from for example sunlight, drought, microorganisms) they speed up their antioxidant production. Stressed plants therefore contain the most antioxidants (DEMMIG-ADAMS and ADAMS, 2002).

Important traits and low heritability, it is precisely such questions, which could be a major field of research for epigenetic approaches, maximizing (1 - h^2).

- treatments with anti-apoptotic substances (chemical industry, fertilizer industry, breeding companies, agricultural engineering companies), special case - survival strategies.

– fresh cut flower food, e.g. Chrystal

Different additives can be used to prolong the lives of fresh cut flowers. Experiments were performed with various substances mixed with water, including aspirin, vitamin pills, vinegar, pennies, ethylene and anti-ethylene treatment and flower food to test their effect on cut flowers' lifespans. (WIKIPEDIA CONTRIBUTORS. Additives for cut flowers [Internet]).

– Monoethanolamine

The effect of monoethanolamine (EA, applied as foliar spray, 10 mg per pot) on grain yield and yield components was investigated in pot experiments with spring barley, winter wheat, and winter rye. Under conditions of a moderate drought stress the applied EA increased the grain yield of spring barley from 5 % to 7 % (significance only at α= 0.05). A stimulating effect of EA on the grain yield of winter wheat and winter rye was also obtained (BERGMANN *et al.*, 1990, 1991).

– Strobilurins: a fitness cocktail

Scientists at Bayer CropScience have discovered that a tried and tested fungicide that has been protecting cereals, vegetables and fruit crops against dangerous fungal diseases for many years also has completely new and extremely useful properties: trifloxystrobin not only successfully protects against harmful fungi, but also increases plants' resistance to stress (BAYER CROPSCIENCE, 2012).

– Anti-apoptotic products in medicine?

Severe pathological consequences of injuries can be largely determined by acute response of damaged tissues, involving excessive loss of cells through the mechanism of programmed cell death (apoptosis). The risk of death or disability can be greatly reduced by suppressing such a deadly reaction. A research program in medicine are aimed at identification and production of factors and their comprehensive testing as tissue protecting agents against injuries, caused by ionizing radiation, acute chemical poisoning, heat shock and hypoxia (GUDOV *et al.*, 2005).

Treatments aiming to inhibit apoptosis do simultaneously inhibit the expression of proapoptotic factors and promote the expression of anti-apoptotic factors (WIKIPEDIA CONTRIBUTORS. Apoptosis [Internet]).

– Gabapentin-Lactam (GBP-L)

Gabapentin-Lactam (GBP-L) was shown to be neuropretective preventing degeneration of neurons when a common feature of conditions such as glaucoma, optic-nerve injury, or retinal ischemia is apoptotic retinal ganglion cell death (JEHLE *et al.*, 2000, LAGRÈZE *et al.*, 2001, PIELEN *et al.*, 2004).

KNÖRLE and STAUSS (2005) showed in 2 trials that Gabapentin-Lactam (GBP-L) prolongs cut flower lifespans of different rose types 3 to 5 days compared to treatments with marketable fresh cut flower food significantly. The differentiation of flowering stages started after the 5th to 7th day.

<u>Work package "Production of public goods (ecosystem functions additionally to food production)"</u>

- Clear water, biodiversity

Agroecosystems are essential sources of provisioning services, and the value of the products they provide are readily measured using standard market analysis. Depending on their structure and management, they may also contribute a number of other ecosystem services (MEA, 2005). Ecosystem processes operating within agricultural systems can provide some of the same supporting services described above, including pollination, pest control, genetic diversity for future agricultural use, soil retention, and regulation of soil fertility, nutrient cycling and water. In addition, agricultural systems can be managed to support biodiversity and enhance carbon sequestration - globally important ecosystem services (POWER, 2010).

A low-input and high-output agriculture achieve maximum results with limited environmental or ecological resources – and so produces food, clear water and biodiversity.

- agriCulture

There are many definitions of culture (KROEBER and KLUCKHOHN, 1952). To select one, culture could be described as: (1) the mind of a cultured person; (2) the process of culturing people; (3) art and intellectual works that might culture a person; and (4) culture as a system that maintains, communicates, and reproduce the characteristics of a society, and that allows for people to participate in it (WILLIAMS, 1981; AXELSSON *et al.*, 2013).

Cultural sustainability has to do with the preservation of our culture, ethics, norms and values. The most important aspect of cultural development is to remind people culture and ethics, regardless of place, origin or belief and to promote culture to avoid extinction. Cultural sustainability also has to do with enabling religious pluralism because not all norms are equally valid though religious beliefs mostly help the society in advancement (CHIZURUM, 2013).

That is cultural sustainability which is the positive stress, the mindfulness (maximization of $1-h^2$) for resilient changes.

<u>Work package "Sustainable Management"</u>

- Reliability, Mindfulness, Resilience

Research reveals that certain organizations have been highly successful in honing their abilities to act reliably and handle adversity. These are called high-reliability organizations (HROs). They include aircraft carriers, nuclear power plants and firefighting crews, which consistently deliver high performance in unpredictable situations where the potential for error and disaster is overwhelming. Although ordinary companies do not face do-or-die circumstances of the same magnitude, they can learn a great deal from HROs about managing their operations effectively under trying conditions so crises can be avoided (WEICK and SUTCLIFFE, 2007).

When things do go wrong, companies must identify and empower those with the expertise to contain or minimize the situation, and then rely upon organizational resilience to bounce back quickly after a misstep. By operating "mindfully" and making critical adjustments in a timely manner, business organizations are better able to manage the unexpected in a challenging, highly competitive environment (WEICK and SUTCLIFFE, 2007).

The basic message of WEICK and SUTCLIFFE (2007 and 2013) is that expectations can get you into trouble unless you create a mindful infrastructure. WEICK and SUTCLIFFE recommend five practices for developing "mindfulness":

1. *Preoccupation with failure.* Encourage the reporting of errors and pay attention to any failures. These lapses may signal possible weakness in other parts of the organization. Too often, success narrows perceptions, breeds overconfidence in current practices and squelches opposing viewpoints. This leads to complacency that in turn increases the likelihood unexpected events will go undetected and snowball into bigger problems.
2. *Reluctance to simplify interpretations.* Analyze each occurrence through fresh eyes and take nothing for granted. Take a more complex view of matters and look for disconfirming evidence that foreshadows unexpected problems. Seek input from diverse sources, study minute details, discuss confusing events and listen intently. Avoid lumping details together or attempting to normalize an unexpected event in order to preserve a preconceived expectation.
3. *Sensitivity to operations.* Pay serious attention to minute-to-minute operations and be aware of imperfections in these activities. Strive to make ongoing assessments and continual updates. Enlist everyone’s help in fine-tuning the workings of the organization.
4. *Commitment to resilience.* Cultivate the processes of resilience, intelligent reaction and improvisation. Build excess capability by rotating positions, creating additional sources of knowledge and adding new skills. Be mindful of errors that have occurred and take steps to correct them before they worsen. Once the fix is made, make every effort to return to a state of preparedness as quickly as possible. Be ready to handle the next unforeseen event.
5. *Deference to expertise.* During troubled times, shift the leadership role to the person or team possessing the greatest expertise and experience to deal with the problem at hand. Provide them with the empowerment they need to take timely, effective action. Avoid using rank and status as the sole basis for determining who makes decisions when unexpected events occur.
6. *Certification with standards in agriculture.* About 5 million hectares of cultivated area are currently certified according to standards. The certification is used as a tool for sustainable development on the basis of aspiring to agricultural ethics (MEIER, 2012). Important in the development of standards is the intercultural discourse between all concerned. Whose foundations are set for scientific knowledge, a strong precautionary principle and on practical experience?

   The agricultural ethics is the question of the costs and burdens. And who pays for this. Serious doubts about the future viability of industrial agriculture there, especially about a billion people go hungry.

   Ethically oriented visions for sustainable environmental, social and cultural development seem to be rather inappropriate for everyday of the current agricultural economic reality today. Too often their central principles are again sacrificed if a market Imputed becomes apparent. Moral, religious or cultural values come back in the age of our economic world order to insignificance.

   Because agricultural ethics, the future-decisive issues on the basis of values, the background of the conflicts are particularly evident in it. This cannot be solved in the continuation of the path. It is a transdisciplinary discourse on the basis of respect for the life required.

- The Luebeck concept of „Nature-Oriented Forest Use“: Factoring non-knowledge into natural resource management

Trying to predict and control outputs in systems where the dynamics are not well known has always been a challenge of forest management. This goal is further complicated by the complexity of interactions at multiple levels. Identification of the vital system attributes and the development of an understanding of the underlying processes, weak links, and critical limits of these processes is a starting point for addressing this challenge by using systems thinking to improve forest resilience. The case studies from Bosque SecoChiquitano and the Luebeck forest highlighted the importance of understanding the linkages between ecological structures and processes, and the associated and economic values and benefits for social systems. In both cases, it was demonstrated that management guided by principles of ecological integrity provided greater economic benefits than a management plan based on objectives for improved efficiency (MCAFEE *et al.*, 2010).

Forest management is related to systems with:

- high complexity and dynamics which are mainly unknown,
- individual living and interacting elements,
- the ability of self-regeneration and adapt to changes,
- extremely long lifespans and production times.

Furthermore, forests are embedded with highly complex (and unpredictable) social, cultural and economic systems. Forest management is a type of economic activity characterized by planning and decision-making in spite of ever persisting knowledge gaps, blind spots and unknowable's (FÄHSER, 2012).

According FÄHSER (2012), basic considerations for the management concept in Luebeck are:

- forests are unknown "black box" systems,
- forest management decisions are decisions made under uncertainty,
- forest management is method of adapting to nature with a nature oriented approach and
- forest managers are cooperative partners in a participatory process with concerned persons and organizations.

Even "ethics" is increasingly introduced into the forest management plans.

Nature-oriented forest use seems to fulfil the notion of having a significantly improved financial result, while meeting ambitious ecological and social demands at the same time. Respectively, this effect is caused by the adaptation to natural processes (instead of substituting nature with artificial forest structures) and by minimizing the impact. Economically, this results in:

- low-input/costs,
- low production risks and diseases,
- low damage to soil and remaining trees,
- high value of the target timber and non-timber products (FÄHSER, 2012).

Discussion

The cultural sustainability (values, appreciation, ethics, customs, agri**C**ulture, ...) as unifying element for the environmental, economic and social pillar is the (positive) stress (maximization of $1\text{-}h^2$) for a paradigm shift in the behaviour of stakeholders (ALTNER, 1992):

- credibility and awareness, life style issues,
- Corporate Social Responsibility,
- low-input with high-output of food and, for example clean water, biodiversity, landscape, agri**C**ulture, ..., and
- win-win situation for the actors of today's intensive agriculture.

How work was carried out?

In the 80s Stauss has rewritten parts of University Stuttgart-Hohenheim lecture notes of Prof. Geiger, Prof. Fewson and Mr. Utz concerning quantitative genetics and selection indices analogous to the environmental point of view as "selection of biologically active substances (as ingredients of the environment) on the basis of quantitative genetics." The "analog invention" was without test results, unfortunately, it could not be patented, but with STAUSS (1992) he succeeded with an "application"-publication for the field of agro-industry. The initial reason of his work at that time was a statement of his superiors at Ciba in Basel that the chemical pesticides and plant regulators industry is the competing sector to breeding.

Recently Stauss realized that he basically had developed a script on "Quantitative Population Epigenetics".

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