

Unpredictable Nature of Environment on Nitrogen Supply and Demand

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ABSTRACT

The second law of thermodynamics states that entropy or randomness in a given system will increase with time. This is shown in science, where more and more biological processes have been found to be independent. Contemporary work has delineated the independence of yield potential (YP0) and nitrogen (N) response in cereal crop production. Each year, residual N in the soil following crop harvest is different. Yield levels change radically from year to year, a product of an ever-changing and unpredictable/random environment. The contribution of residual soil N for next years' growing crop randomly influences N response or the response index (RI). Consistent with the second law of thermodynamics, where it is understood that entropy increases with time and is irreversible, biological systems are expected to become increasingly random with time. Consequently, a range of different biological parameters will influence YP0 and RI in an unrelated manner. The unpredictable nature that environment has on N demand, and the unpredictable nature that environment has on final grain yield, dictate the need for independent estimation of multiple random variables that will be used in mid-season biological algorithms of the future.

Core Ideas

- Randomness in biological systems is increasing.
- Many biological processes are independent.
- Yield levels change from one year to the next.
- Environments change over time and are random.
- Optimum fertilizer nitrogen rates change dramatically from year to year.

GREGOR JOHANN Mendel (1822–1884), a Catholic Augustinian Priest, is considered to be the founder of the modern science of genetics (Olby, 1997). He discovered the basic principles of heredity through multiple experiments with peas (*Pisum* sp) but suggested that this theory applied to all living things. Mendel's Law of Independent Assortment established that traits were passed on independently of other traits from parent to offspring (Bateson, 2007). During meiosis, the pairs of homologous chromosomes are divided in half to form haploid cells, and this separation, or assortment, of homologous chromosomes is random (Scitable, 2018). Randomness is the fundamental and overarching principle that helps to explain how traits were independently passed from parent to offspring. It is the presence of randomness in all biological systems that this paper aims to highlight.

BIOLOGICAL INDEPENDENCE IN AGRICULTURE

Early biology work coming from Hastings and Sweeney (1957) noted that it was important to understand that temperature independence supported the concept that a diurnal rhythm could be related to a biological timing device or clock. This was some of the first work to establish that similar biological processes can be independent.

Raun et al. (2011), using 90 site-years of winter wheat data, reported that yield potential (YP0) and N response, or response index (RI), were independent. Ensuing work by Arnall et al. (2013), derived from 261 site-years of both maize and wheat data, further documented the validity of this finding. This concept was coupled with results from Dhital and Raun (2016) that recognized highly variable optimum N rates and actual yield increases due to N from year to year and location to location in maize-growing regions of the United States. They further showed highly variable yield levels in both the check (0-N) and adequately fertilized plots. This comprehensive study included data from Colorado, Iowa, Kentucky, Maryland, Missouri, Nebraska, Texas, and Wisconsin and encompassed yield records from research field trials totaling 213 site-years. Published results included in this work spanned the years 1958 to 2010. Dhital and Raun (2016) also showed that optimum N rates were not correlated with either the high-N rate yield or the 0-N check plot yield.

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Abbreviations: RI, response index; NUE, nitrogen use efficiency; YP0, yield potential with no N fertilization.

The yield level from one year to the next was documented to be random and unpredictable, and the response to fertilizer N year to year was also random (Dhital and Raun 2016; Lamb et al., 1997). Another related study showed that temperature sensitivity for soil respiration is likely independent of the mean annual temperature of the soil, and this was observed over a wide variety of ecosystems and average temperatures (Giardina and Ryan, 2000).

La Roche et al. (1996) documented the importance of independence in biological systems when reporting that, although higher plants and prochlorophytes share common pigment complements, their light-harvesting systems have evolved independently. More relevant to this paper, Arnall et al. (2013) showed that wheat and maize grain yield levels and the response to fertilizer N were independent. Because both affect the demand for fertilizer N, independent estimates of both were suggested to calculate realistic in-season fertilizer N rates.

Nitrogen (N) fertilization has traditionally taken place before planting or preplant in wheat and corn production systems (Fageria and Baligar, 2005). Applying all N preplant has been heavily scrutinized because it is one of the most inefficient methods of applying this source (Bushong et al., 2014; Raun et al., 2002). Misuse of N fertilizer has been exacerbated in Iowa, where the local Water Works facility that supplies water for the city of Des Moines filed a lawsuit against surrounding farmers for applying excess N that ended up in drinking water supplies (Erbenraut, 2017). Babcock (1992) noted that the motivation for increasing N fertilizer application is self-protection as farmers find it profitable to reduce the probability that they might be “caught short” of fertilizer.

The development of methods for improving N fertilization, especially those that increase N use efficiency (NUE), remains important. Considering that world NUE for cereal crop production is estimated at 33%, Raun and Johnson (1999) delineated several methods to improve this value, including sidedress or topdress N applied in the middle of the growing season. When winter wheat was grown in a forage-only production system, NUE values approached 66% (Thomason et al., 2002). This was due in part to harvesting all plant matter before the flowering stage when plant N loss is expected (Kanampiu et al., 1997).

ENTROPY AND RANDOMNESS

Early work by Mann (1970) recognized randomness in fundamental biological processes and organic evolution. He further suggested that randomness is inherent in the natural process. Entropy is also a gauge of randomness or chaos within a closed system. As usable energy is irretrievably lost, disorganization, randomness, and chaos increase (All About Science, 2018). This is aligned with the second law of thermodynamics, which embeds knowledge that the total entropy of an isolated system can never decrease over time, where entropy is the degree of disorder or randomness in the system (Costa et al., 2002).

Early work by von Bertalanffy noted that “From the physical point of view, the characteristic state of the living organism is that of an open system” (von Bertalanffy, 1950). Furthermore, the theory of open systems opens a new field in physics, and this development is more remarkable because thermodynamics seemed to be a consummate doctrine within classical physics. In biology, the nature of the open system is at the basis of

fundamental life phenomena, and this conception seems to point the direction and pave the way for biology to become an exact science (von Bertalanffy, 1950).

Longo and Montévil (2012) noted that randomness was an essential component of biological variability and was associated with the growth of the biological organization. Related work by Brooks et al. (1989) reported that all conservative transformations in biological systems are coupled with the presence of heat-generating transformations. They also reported that inherent biological production, or genealogical processes, are entropic. Heams (2014) reported that randomness is, in many ways, an inherent feature of evolutionary biology and genetics. This is reflected in work by Lee (2002), who noted that the invasion success of many species depends on their ability to respond to natural selection. Wang et al. (2016) summarized that the second law of thermodynamics states that a system progresses in the direction of increasing entropy, where a system includes engineered devices as well as biological organisms, and that entropy is a measure of randomness. He further noted that a system naturally progresses from nonrandomness to randomness.

When referencing the second law of thermodynamics, von Bertalanffy (1950) noted that, in natural processes, the total entropy always increases, and the process is irreversible. This increase in entropy accounts for the irreversibility of natural processes. Udgaonkar (2001) observed that the second law of thermodynamics does not distinguish between living and nonliving things, further observing that the concepts of thermodynamics constitute the unifying principles of physics, chemistry, and biology. He further noted that those processes that lead to randomness and disorder would appear to be out of place in the world of biology. Udgaonkar (2001) also reported that the second law of thermodynamics implies that the principle of total entropy, as a measure of disorder, must steadily increase. This acknowledgment, which included biology, further ties the second law of thermodynamics to plant and crop production systems. Heams (2014) commented on the need for a reappraisal of the status of randomness in life sciences, which would have important consequences for research strategies in theoretical and applied biology.

For this manuscript, the second law of thermodynamics helps to explain why ostensibly similar biological components (RI and YP0) were independent (Arnall et al., 2013; Raun et al., 2011). This law delineates that everything is becoming increasingly random with time. In the context of this paper, it is understood that a range of different variables/factors/biological components will each influence YP0 and RI differently.

Considering Mendel’s Law of Independent Assortment (traits passed on independently) and the second law of thermodynamics, the overarching impact/influence of randomness on all biological properties leads to understanding that any one of these biological variables should not be related.

For example, excess N fertilizer can decrease grain yields but in the process leaves excess N in the soil or residual N that can positively or negatively affect yield in ensuing years (Wang et al., 2011). This concept, explained as “synchrony” of N supply, documents why overapplication of N can adversely affect yield and the immediate environment yet lead to increased residual N (Fageria and Baligar, 2005). This same phenomenon was indirectly described by Wang et al. (2011), where subsequent year residual N was aided by current season overapplication that

decreased in-season wheat grain yields. Stanford (1973) also highlighted the perils of overapplication of N and that it leads to reduced NUE.

Schepers and Holland (2012) stated that a yield component is not necessary for the development of an in-season recommendation algorithm. Nonetheless, their data showed dramatic differences in yield level from year to year and that these differences would ultimately affect final N demand. Actual N rate has been tied to yield level in numerous papers showing a positive correlation between crop N demand and grain yield (Fageria, 2014; Schepers et al., 1992).

Work by Lamb et al. (1997) showed dramatic differences in yield level and the range in yields over time. Furthermore, grain yields were not spatially consistent from year to year. More noteworthy was the finding that specific areas in the field of study that had higher yields or lower yields were not consistent over time.

Global estimates of phosphorus (P) (Dhillon et al., 2017), potassium (K) (Dhillon et al., 2019), and sulfur (S) (Aula et al., 2019) use efficiencies in cereal crops have been found to be highly variable from one year to the next. Phosphorus use efficiency in cereal crops was found to be 16% on average over a 53-yr period (range, 12–21%) (Dhillon et al., 2017). Similarly, over a 55-yr period, potassium use efficiency averaged 19% (range, 15–26%) (Dhillon et al., 2019). Likewise, sulfur use efficiency averaged 18% (range, 14–22%) (Aula et al., 2019). In summary, these citations reflect the randomness and unpredictable nature of yields across the globe and associated use efficiencies.

IMPORTANCE OF RANDOMNESS

The terms “stochastic process” and “random process” are used interchangeably. Randomness is the lack of pattern or predictability. Saunders and Ho (1976) noted that a striking feature of evolution is that it tends to produce organisms that are more and more complex and as such more and more random.

Systems do not necessarily tend toward chaos but to a situation that is inherently unstable and unpredictable. At any given moment, random variations occur, with varying consequences and varying degrees of predictability (Spielman et al., 2009).

Tumusiime et al. (2011) reported that yield potential and N response vary randomly from one year to the next. Similarly, when Mills et al. (2017) attempted to predict the year-to-year variation in response to applied N using environmental variables like rainfall, predictability was low. Supporting work by Huang et al. (2016) documented highly variable atmospheric N deposition from year to year, which influenced N demand for the ensuing year.

Jokela and Randall (1997) showed that fertilizer-derived N from the soil ranged from 25 to 56%, with a large proportion at the high N rate in inorganic forms. Residual uptake of fertilizer-derived N by grain ranged from 1 to 10% of the initial N rate, and this rate changed dramatically by year. Prior work by Jokela and Randall (1989) reported that residual $\text{NO}_3\text{-N}$ in the soil profile (1.5 m) of the 0-N check plot (no N applied) varied significantly over time and was unpredictable (range, 67–215 kg N as $\text{NO}_3\text{-N}$ from 1982 to 1984). This same result was observed in plots receiving added fertilizer N.

Similar work by Olson et al. (1976) showed that residual mineral N influenced both wheat and corn grain protein levels and that these levels were noticeably different by environment. Raun

et al. (2017) noted an unpredictable environmental influence on grain yields and suggested predicting mid-season yield potential using optical sensors to improve in-season cereal fertilizer N recommendations over that of yield goals.

An alternative N fertilizer recommendation method that remains popular includes maximum return to N (Sawyer et al., 2006). This procedure estimates economically optimum N rates using historical crop response adjusted for current grain and fertilizer prices.

The importance of randomness in biological systems was discussed by Jalan (2015), who further delineated this concept using examples coming from biological sciences. Kallenberg (2002) noted that random measures occur everywhere in our discipline and play a fundamental role in practically every area of stochastic or random processes. Work by Thrupp (2000) highlighted the importance of increased agrobiodiversity for sustaining food security. This work further noted that conflicting agricultural politics that promote monocultural industrial farming/uniform technology should be eliminated.

VARIABILITY IN RESIDUAL NITROGEN

Work by Onken et al. (1985) documented that residual soil N fluctuated unpredictably from year to year. This very same result was reported by Jokela and Randall (1989), who reported that residual N was affected by random environmental effects.

Work by Bundy and Malone (1988) demonstrated that soil profile $\text{NO}_3\text{-N}$ influenced maize response to applied N. They further noted that annual adjustment of N recommendations for profile $\text{NO}_3\text{-N}$ should be made especially when substantial overwinter carryover of profile $\text{NO}_3\text{-N}$ occurs. Important to this work was that profile $\text{NO}_3\text{-N}$ was highly variable over years and locations sampled (Bundy and Malone, 1988). Onken et al. (1985) conveyed that, to maximize fertilizer use efficiency at a given yield level, it would be necessary to minimize residual soil $\text{NO}_3\text{-N}$. Some of these processes are random and largely governed by changes in the environment in addition to management practices (Di and Cameron, 2016).

Spitz and De Vos (1983) noted that topdress N should be based on residual soil N and the environment-specific N requirement. They further showed that both the environment and residual soil N vary considerably by environment. Alarming work from China by Liu et al. (2013) noted that the impact of atmospheric N deposition on their ecosystems includes increased plant foliar N concentrations and increased crop N uptake from long-term unfertilized croplands. They further discussed a continuing challenge to reduce emissions of reactive atmospheric N and the associated N deposition, which has negative effects on human health and the environment.

ENVIRONMENT

Over 8 yr (1991–1998), Herron et al. (1968) reported that total rainfall at North Platte, NE, ranged from 477 to 723 mm, with the low and high occurring in consecutive years (1995 and 1996). Work by Salvagiotti et al. (2008) demonstrated that the environment dictated the availability and subsequent demand for N in soybean [*Glycine max* (L.) Merr.] production systems. The impact of environment on crop N demand was further noted to be variable from one year to the next. It was also reported that soybean yield was more likely to respond to N

fertilization in high-yielding environments. Chen et al. (2004) found that increases in rainfall and temperature increased yield levels but contributed to increased sorghum yield variability.

A consequence of unpredictable weather effects on crop requirements has been to use reference plots (high N rates) and crop sensing before in-season N application (Tremblay and Belec, 2006). This is bound to the understanding that weather (particularly rainfall in dryland production systems) is the primary driver for both plant growth and soil nutrient availability and that weather changes dramatically from year to year. This has in turn been reflected in unusually high check plot yields that have been observed over time in many long-term experiments (Davis et al., 2003; Dhital and Raun, 2016)

Arnall et al. (2013) further demonstrated the randomness and inconsistency of N response over time, which was observed in all long-term experiments described in their paper, which had been performed in Iowa, Nebraska, Wisconsin, and Oklahoma. They estimated N response using RI by dividing grain yield in the adequately fertilized plots by grain yield in the unfertilized plots.

Lory and Scharf (2003) studied 298 N response experiments over five states (Illinois, Minnesota, Missouri, Pennsylvania, and Wisconsin). For 105 of the 298 locations, the economic optimum N rate was zero, meaning that those sites were non-responsive to applied N. Their work also showed that fertilizer recommendation systems that rely only on yield or ignore yield entirely are limited to explaining <50% of the variation in economic optimum N rates.

DISCUSSION

Without having an N-rich strip and an estimate of the RI (Mullen et al., 2003), methods that are currently used cannot accurately predict either YP0 or crop responsiveness to N prior to crop establishment (Dhital and Raun, 2016; Magdoff, 1992; Raun et al., 2017). If yield levels change from year to year and are random and unpredictable, there should be no defined relationship between YP0 and RI. As per the work of Stevens et al. (2005), N mineralization is expected to supply random, unpredictable quantities of inorganic N from one year to the next. The influence of other N components within the N cycle, on N demand, should also be random, including (but not exclusive to) rainfall, ambient temperature, soil type, soil organic matter, and humidity.

Rosenberg (1987) delineated the irregular distribution of rainfall over space and time in the Great Plains. His work further documented that atmospheric demand for water from growing plants is strong and generally exceeds the supply of natural precipitation. Maithani et al. (1998) consistently showed that the interaction of rainfall and temperature on N mineralization and grain yield were random. One important aspect of extreme short-term events that surround climate change is the apparent randomness and abruptness with which they have arrived (Salinger et al., 2000). With all the atmospheric/biological/agronomic variables that are known to be random, it is not surprising as to why they are not related. If it can be established that they are unrelated (YP0 and RI) and if “random” is accepted as a primary control variable, independent estimates of basically everything are in order, not just YP0 and RI.

One of the reasons that yield potential and N response are independent is that residual N from the previous year is always different and likely random due to last year’s environment

(Jokela and Randall 1989). The contribution of residual N for the ensuing year then affects the ensuing years’ RI randomly but does not necessarily affect yield level unless it was a good year (no moisture stress). This concept is articulated in results from Dhital and Raun (2016), which showed highly variable optimum N rates from year to year and location to location over all the Great Plains states evaluated. This was also tied to the unpredictable nature of the environment on N demand.

If the prior year was a bad year (for yield) and significant quantities of residual N were present, the RI should be low (limited N demand due to high residual N). What makes sense is the random nature of yield level and the random nature of RI. However, each is theoretically influenced by different years (yield by the current year and RI by the previous year). Because each is random, it makes sense as to why YP0 and RI would seldom be related (over time). Long-term nutrient management experiments allowed scientists to test this concept (independence of YP0 and RI), which was verified in both wheat and maize trials (Arnall et al., 2013; Raun et al., 2011).

Biological reasons that explain why YP0 and RI are independent of one another include knowing that there are wetter-than-normal years when yield levels are high but where limited N response to fertilizer has been reported (Raun and Johnson, 1999; Raun et al., 2011). Similarly, finding large increases in yield from applied N in mild/dry years is not unusual (Girma et al., 2007). The unpredictable nature of the environment was evident at Arlington, WI, where the check plot yielded 5.6 Mg ha⁻¹ in 1995. Considering that no N had been applied for 37 yr, it was somewhat surprising to find a check plot yield that was 60% of the highest yield observed in 1995 (9.5 Mg ha⁻¹) (Bundy et al., 2011). Similarly, near-maximum yields were randomly observed in check plots having received no fertilizer N for many years at all sites (Dhital and Raun, 2016).

The unpredictable nature that environment has on N demand and the unpredictable nature that environment has on final yield dictate that both be estimated independently of one another.

RECOMMENDATIONS

Continued use of historical crop response to N rates such as the maximum return to N will unlikely address the randomness of processes and the expected year-to-year variability in optimum N rates (Dhital and Raun, 2016). In the future, algorithms are likely to take on independent estimates of more and more properties. If these individual properties are known to affect the output parameter (e.g., estimate of fertilizer N rate), each should be estimated independently because they are becoming increasingly random with time.

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