**Independence of Biological Processes in Agriculture**

**Abstract**

Current knowledge suggests that biodiversity and randomness will increase. This is reflected in findings that more and more processes have been found to be independent. More contemporary work 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 2nd law of thermodynamics where it is understood that total entropy or orderliness increases with time and is irreversible, biological systems are expected to become more and more random with time.  Consequently, a range of different biological parameters will each 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.

**Introduction**

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 (Pisium 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 (<https://www.nature.com/scitable/definition/principle-of-independent-assortment-law-of-independent-302>, visited, October 4, 2018). Random is the fundamental/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. Essentially this was some of the first work to establish that similar biological processes can be independent.

Yield Potential (YP0) and N response or Response Index (RI) were reported to be independent by Raun et al. (2011), using 90 site-years of winter wheat data. Ensuing work by Arnall et al. (2013) coming 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 US. They further showed highly variable yield levels in both the check (0-N) and adequately fertilized plots. This comprehensive study included data from CO, IA, KY, MD, MO, NE, TX and WI, and encompassed yield records from research field trials totaling 213 site-years. Published results included in this work spanned the years of 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.

The yield level from one year to the next was documented to be random and unpredictable, while the response to fertilizer N year to year was also random (Dhital and Raun 2016; Lamb et al., 2013). Another related study showed that temperature sensitivity for soil respiration is likely independent of the mean annual temperature of the soil and this 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 in order to calculate realistic in-season fertilizer N rates.

Nitrogen (N) fertilization has traditionally taken place prior to planting or preplant in wheat and corn production systems (Fageria and Baligar, 2005). Applying all N preplant has been heavily scrutinized as 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 law suit against surrounding farmers for applying excess N that ended up in drinking water supplies (Erbentraut, 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 nitrogen 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 prior to the flowering stage when plant N loss is expected (Kanampiu et al., 1997).

**Entropy and Randomness**

Early work by Mann (1970) recognized randomness in basic 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. (<https://www.allaboutscience.org/second-law-of-thermodynamics.htm>, visited June 19, 2018). This is aligned with the second law of thermodynamics that embeds knowledge that the total entropy of an isolated system can never decrease over time, where entropy is understood as the degree of disorder or randomness in the system.

In all spontaneous processes, the total entropy always increases and the process is irreversible. The increase in entropy accounts for the irreversibility of natural processes, and the asymmetry between future and past. (Wikipedia, Second law of Thermodynamics, June 19, 2018).

Udgonkar (2001) noted that the second law of thermodynamics does not distinguish between living and non-living things, further observing that the concepts of thermodynamics constitute the unifying principles of physics, chemistry and biology. This final credit including biology, further ties the second law of thermodynamics to plant and crop production systems. Heams (2014) noted the need for a reappraisal of the status of randomness in life sciences, and that have important consequences for research strategies in theoretical and applied biology.

Moreover, the 2nd law of thermodynamics helps to explain why ostensibly similar biological components (RI and YP0) were actually independent (Arnall et al., 2013; Raun et al., 2011).  This law delineates that everything is becoming more and more 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.

Combining Mendel’s Law of Independent Assortment, and the 2nd law of thermodynamics superimpose the overarching impact/influence of randomness on all biological properties. As such, expecting any one of these biological variables to be related is much less probable and unrealistic.

For example, excess N fertilizer can actually decrease grain yields, but in the process, leave excess N in the soil or residual N that can positively/negatively impact yield in ensuing years. This concept explained as ‘synchrony’ of N supply, documents why over-application 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 over-application that decreased in-season wheat grain yields. Stanford (1973) also highlighted the perils of over application of N, and that leads to decreased use efficiency.

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, year to year, and that would ultimately impact final N demand. Actual N rate has been tied to yield level in numerous papers showing a positive correlation between crop N demand and yield (Fageria, 2014; Schepers et al., 1992).

Work by Lamb et al. (2013) showed dramatic differences in yield level and the range in yields over time. Grain yields were further not spatially consistent from year to year. More noteworthy was finding that those specific areas in the field of study that had higher yields or lower yields were not consistent over time.

**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 which are more and more complex, 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 and that influenced ensuing year N demand.

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 that changed dramatically by year. Prior work by Jokela and Randall (1989) reported that residual NO3-N in the soil profile (1.5m) of the 0-N check plot (no N applied), varied significantly over time, and that was unpredictable (range of 67 to 215 kg N as NO3-N, from 1982 to 1984). This same result was observed in plots receiving added fertilizer N.

Similar work by Olson et al. (1975) showed that residual mineral N influenced both wheat and corn grain protein levels, and that was 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.

The importance of randomness in biological systems was discussed by Jalan (2015) and where this was further delineated using examples coming from the 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.

**Variability in Residual Nitrogen**

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

Work by Bundy and Malone (1988) demonstrated that soil profile NO3-N influenced maize response to applied N. They further noted that annual adjustment of N recommendations for profile NO3-N should be made especially when substantial overwinter carryover of profile NO3-N occurs. Important to this work was that profile NO3-N was highly variable over years and locations sampled (Bundy and Malone, 1988). Onken et al. (1985) conveyed that in order to maximize fertilizer use efficiency, at a given yield level, it would be necessary to minimize residual soil NO3-N. Some of these processes are random and largely governed by changes in environment, in addition to management practices (Di and Cameron, 2002).

Spiertz and De Vos (1983) noted that topdress N should be based on residual soil nitrogen and on the environment-specific N requirement. They further showed that both the environment and residual soil N vary considerably by environment. Alarming work coming from China 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 (Liu et al., 2013). They further reported a continuing challenge to reduce emissions of reactive atmospheric N, and the associated N deposition that has negative effects on human health and the environment.

**Environment**

Over an eight-year period (1991 to 1998), Herron et al. (1999) reported that total rainfall at North Platte, NE ranged from 477 to 723 mm, with the low and high falling in consecutive years (1995, 1996).

Work by Salvagiotti et al. (2008) demonstrated that environment dictated the availability and subsequent demand for N in soybean production systems. The impact of environment on crop N demand was further noted to be variable from one year to 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 that 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 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 and that was observed in all long-term experiments in their paper, coming from Iowa, Nebraska, Wisconsin and Oklahoma. They estimated N response using a Response Index (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, including Illinois, Minnesota, Missouri, Pennsylvania, and Wisconsin. For 105 of the 298 locations, the Economic Optimum N Rate (EONR) 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 less than 50% of the variation in economic optimum N rates.

**Discussion**

Optimum N rates change, are random, and unpredictable. If the yields change as well and are random and unpredictable, then they are likely to be unrelated (YP0 and RI). As per the work of Stevens et al. (2005), N mineralization is expected to deliver 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/or grain yield, were random.

One important aspect of short-term extreme 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 “random” is accepted as an overarching 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 because residual N from the previous year is always different (random due to last year’s environment (Jokela and Randall 1989).  The contribution of residual N for the ensuing year then impacts the ensuing years’ RI, randomly, but that doesn’t necessarily impact yield level, unless it was a good year (no moisture stress).

This concept is articulated in results from Dhital and Raun (2017) that 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.  But, 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), and that was verified in both wheat and maize trials (Arnall et al., 2013; Raun et al., 2011).

Biological reasons that explain why yield potential and N responsiveness 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 et al., 2009; Raun and Johnson, 1999). 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 years, 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 independent of one another. Furthermore, algorithms of the future are likely to take on independent estimates of more and more properties. If these individual properties, are known to impact and/or affect the output parameter (e.g., estimate of fertilizer N rate), each should be estimated independently because they are becoming more and more random with time.

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