Simulating the influence of crop spatial pattern on canola yield

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Abstract

The current non-uniform crop spatial distributions of individual cereal plants and wider-spaced row crops like maize and sugar beet can limit crop performance because of non-optimal resource utilization. The aim of the present study was to investigate the potential influence of two-dimensional crop plant uniformity on the yield of oil seed rape. Voronoi polygons (tessellations) which define the area closer to an individual than to any other individual were used as a measure of the area available to each plant, and corrections were included for extreme polygon shape and eccentricity of the plant location within the polygon. These adjusted polygon areas were used to investigate the potential influence of two of the most important determinants of crop sowing spatial uniformity: row width and longitudinal spacing accuracy, on yield per unit area, and to ask how changes in seeding technology would influence crop performance. The potential for increased yield with improved seeding technology was shown. The results suggest that precision seeding can increase yield by 10 %.

Keywords: modeling, seeding technology, intra-specific competition

Introduction

A central goal of technology in agriculture is to optimize crop growth by optimizing resource utilization. The current uneven ("clumped") crop spatial distributions of individual crop plants can limit crop performance because (i) resources like nutrients and water are not divided among all crop plants in an optimal way, (ii) intra-specific competition within the crop populations starts very early in crop development and (iii) the suppression of weeds is limited by the crop spatial structure. The degree of spatial uniformity (evenness) of seeds sown is primarily determined by the inter-row distance (row width) and the distribution of plants within the row.

Seeding machines differ in their within-row spacing accuracy, which is primarily determined by the seed metering technology. Other machine components, such as seed tubes and coulters, can also influence spacing accuracy (Heege & Billot, 1999). For grain drills with mechanical bulk metering or pneumatic conveying, the distribution of distances between adjacent individuals within a row can be described by a random exponential distribution (Poisson process) with CV = 1.0, which means the standard deviation equals the mean in spacing between individuals in the row.

When grain drills are used to sow oil seed rape (canola; *Brassica napus* L.), the variation in spacing is often greater (CV between 1.2 and 1.5). This is because of (i) suboptimal design of the metering wheel for the low seeding rates (1.0 kg ha^{-1} rather than 100 kg ha^{-1} for which the machines are primary designed) and (ii) mechanical interference from fine powder arising from seed coat abrasion (Griepentrog, 1995; Steffen *et al.*, 1999).

Precision drilling gives a much better spatial seed distribution but is commonly used only for widely spaced crops such as maize and beets with a plant density of less than 20 m^{-2}. With more closely-spaced crops like cereals and oil seed rape with row spacing of 0.10 to 0.12 m, precision drilling is too expensive. For precision drills, variation in spacing occurs due to imperfect dosing (missing or double seeds) and seeds that do not emerge. The evenness of plant spacing for precision seeding results in *CV*s of less than 0.50 and the frequency distribution of spacing within the row often has several modes, which are multiples of the mean or adjusted spacing (Griepentrog, 1992).

There have been several studies on the performance of sowing machinery and the resultant crop patterns of seedlings, but most of these have addressed only seed placement or resultant plant spacing within the row with one-dimensional analyses (Panning *et al.*, 2000; Pasternak *et al.*, 1987). The implicit assumption is that a more even within-row spacing will result in a more uniform two-dimensional spatial pattern.

There are three general categories of two-dimensional point patterns: (i) uniform (hyperdispersed), (ii) random, and (iii) clumped (aggregated; Diggle 2003). It would be ideal if we could describe the degree of two-dimensional spatial uniformity of crop plants with a single measure on a continuous scale that is independent of the sowing method used. There have been some two-dimensional spatial analyses of plant patterns based on different uniformity indices (Mead, 1966; Heege, 1993; Griepentrog, 1995; Kristensen *et al.*, 2006). Mead (1966) used Voronoi polygon tessellations (also called Thiessen polygons or tiles), which delimit the area on the plane closer to each point than to any other point, to visualize and quantify individual "available" areas for carrot plants. He also defined parameters to describe the polygon shape and the position of the plant within the polygons (eccentricity).

The aim of the present study was to investigate the potential influence of spatial crop plant uniformity on the yield of oil seed rape, using Mead's (1966) approach. We explore the potential influence of the two most important determinants of crop sowing spatial uniformity: row width and longitudinal spacing accuracy, on yield per unit area, to ask how changes in seeding technology would influence crop performance. The parameters we varied are rectangularity (ratio of row distance and mean intra-row spacing) and the coefficient of variance of the within-row plant spacing (*CV*). First, we simulate spatial crop plant patterns and compare the simulated patterns to field experiments and measurements of seeding machinery performance. We then use results from published field experiments on the relationship between individual plant yield and available area (Geisler & Stoy, 1987), adjusted for extreme shapes and eccentricities, to predict yield of dry matter per unit area for the different simulated sowing patterns. The overall aim is to provide useful information for the choice, settings and possible modifications of seeding machinery.

Materials and methods

Simulated crop spatial patterns

The simulations of plant locations were based on the two central sowing parameters (1) row width and (2) within-row seed spacing uniformity that determine the 2-dimensional spatial uniformity. The first is expressed by the rectangularity (*q*) defined as row width divided by mean plant spacing within the row and the second by the coefficient of variance (*CV*) of spacings between adjacent plants within the row. The use of rectangularity makes the analyses independent of plant density. We simulated x-y-referenced point patterns and then generated Voronoi polygon tessellations from these patterns.

The different 2-dimensional spatial point patterns were generated by varying (i) rectangularity in the range of 0 to 6 in ≤0.5 increments and (ii) *CV* in the range of 0 to 1.5 in about 0.25 increments to simulate common and other possible row sowing patterns, and then analyzed the resulting point patterns. These parameter ranges are regarded as typical and possible patterns for crop establishment (Griepentrog *et al.*, 2009).

The within-row plant spacing distributions were generated with randomized inverse cumulative density functions (CDF) as described by Devroye (1986). The CDFs are primarily based on results from laboratory tests of different seeding machines (Griepentrog, 1995). Within-row *CV*s of 0 to 0.75 are typical for precision seeders while *CV*s of 0.75 to 1.50 often describe the performance of conventional grain seeders with bulk metering. The longitudinal seed positions in a row are independent of other rows (i.e. rows are not synchronized). Transverse deviations from an ideal straight line were added by a randomized normal distribution with a standard deviation 0.01 m and truncated at ± 0.02 m.

Thus, the generated patterns consisted of four different stochastic variables (i) transversal first row position, (ii) longitudinal start position of all rows, (iii) seed spacings within the rows and (iv) lateral deviation of all seeds. The seeding density was set at 60 m^{-2} and the size of the virtual fields were set to contain approximately 10 000 seeds resulting in 12.91 m by 12.91 m area.

Estimating canola growth and yield

To investigate how crop plants react to variation in polygon area size, shape and eccentricity, canola was chosen. Canola is currently sown with machinery of varying performance including precision seeders and bulk grain seeders with different row width settings.

Geisler & Stoy (1987) conducted field experiments with varying densities and seeding dates. They analyzed yield per area as well as yield components for individual canola plants. The relationship between single plant yield m [g] dry matter and available area A [mm^2] from these trials can be described by an equation from a regression analysis (Griepentrog, 1995; Hühn, 2001):

$$m = k_1 + k_2 \ln(A) \tag{1}$$

The *k*-values for the function are k_1 = - 84.8 and k_2 = 9.707.

These values were used for computing the canola dry matter yield per area. Hühn (2001) also used equation (1) to define the relationship between individual plant yield and available area for different canola varieties. Hühn (2001) gives different values for k_1 and k_2 as a result of data from extensive field experiments including a polygon analysis for individual plant areas. The *k* values from Hühn (2001) for k_1 and k_2 are similar to the values used in this study.

Area was not expected to be the only aspect of a polygon that will affect plant growth. The shape of the polygon and the position of the plant within it can also be expected to have an effect (Mead, 1966). Although canola has the ability to adapt to various above-ground spatial conditions through plasticity in growth, resource utilization will probably be limited for extremely elongated polygons and highly eccentric location within the polygon, which will be common at high values of *CV* and rectangularity.

Pattern of plants at harvest

For simplicity, we assumed no crop plant losses due to seed germination, emergence or other factors. It is well known that stand densities at harvesting time are lower than seeding densities. Geisler & Stoy (1987) report a 20 % overall plant density difference between seeding and harvesting for the common sowing density of 60 seeds m^{-2}. Local crowding increases intra-specific effects and causes seedling mortality early in crop establishment. We simulated this effect by randomly removing one of two individuals when pairs were closer than a minimum distance. This procedure was repeated until there were no plant pairs closer than the minimum distance. The minimum distance value was calculated as a radius of a circular area of 10 000 mm^2, which corresponds to the smallest area predicting yield > 0 in equation (1). After modifying the point pattern for the minimum distance, the Voronoi tessellations were generated for the resultant point pattern. In addition to area, we calculated the compactness (*C*) of each polygon and eccentricity (*E*) of the point within it. Compactness (Bribiesca, 1997) is defined as

$$C = \frac{s^2}{A} \tag{2}$$

Where s is polygon circumference and A polygon area.

We standardize the measure of compactness relative to that of the most uniform of all 2-dimensional point patterns, the hexagonal ("bee-hive") pattern:

$$C_{hexagon} = \frac{C(polygon)}{C(hexagon)} = \frac{C(polygon)}{8\sqrt{3}} = \frac{s^2}{8\sqrt{3} * A} \tag{3}$$

Mead (1966) defined the eccentricity of a plant position within a polygon:

$$E = \frac{|MP|}{D} \tag{4}$$

where $|MP|$ is the distance between M , the centroid (center of mass) of the polygon and P the plant position, and

$$D = \frac{\sum a_i |MV_i|}{\sum a_i} \tag{5}$$

where outer angle $a_i = \pi - b_i$, with b_i as inner angle and $|MV_i|$ is the distance between M and vertex V_i of the polygon.

<u>Yield prediction</u>

Vandermeer (1984) argued that the intensity of competition is constant within a specifiable region surrounding each plant. To account for extreme polygon shapes and extremely off-centered points, the correction factors k_{shape} and $k_{eccentric}$ are introduced:

$$k_{shape} = f(C_{hexagon}) = \begin{cases} 1 & C_{hexagon} \leq 1.5 \\ 1 - 0.4(C_{hexagon} - 1.5) & 1.5 < C_{hexagon} \end{cases} \tag{6}$$

$$k_{eccentric} = f(E) = \begin{cases} 1 & E \leq 0.2 \\ 1 - 0.4(E - 0.2) & 0.2 < E \end{cases} \tag{7}$$

The corrected single plant yield is calculated from equation (1) as follows:

$$m_{corrected} = m \times k_{shape} \times k_{eccentric} \tag{8}$$

The final uncorrected and corrected area yield after Voronoi tessellation is calculated by:

$$Y = \frac{\sum m_i}{\sum A_i}$$
9)

In order to avoid border effects, only those polygons which did not touch the predefined field boundaries were used in equation (9).

The mean effective correction factors k_{shape} and $k_{eccentric}$ are calculated by dividing the results of the corrected by the uncorrected area yield values for the given ranges of *CV* and rectangularity. For calculating the effective values for k_{shape} and $k_{eccentric}$ versus *CV* and rectangularity, the k values of one was set to 1.0 for calculating the other (equations 6 and 7).

All simulations were performed in MATLAB (MathWorks, Natick, MA, USA) as M-files (scripts and functions). The model is flexible with respect to plot size and shape. There were 10 replicate runs for each set of parameter settings, and the average yield from each variant was used in the analyses.

Results and discussion

From crop management practice, it is well known that there is a decrease in density between harvest and field emergence patterns (Geisler & Stoy, 1987), and this is reflected in our simulations (Fig. 1). One reason is intra-specific competition between close neighbor plants during the vegetation period, another is plant mortality due to predation and diseases. Mortality due to intra-specific competition generates increased spatial evenness (Stoll & Bergius, 2005), and we simulated this by removing individuals with very close neighbors. A within-row aggregated pattern ($CV > 1.0$) and high rectangularity ($q > 4.0$) resulted in the lowest estimated yields, as Mithen *et al.* (1984) showed for experiments on *Lapsana communis L.*

Estimated yield based on polygon areas alone was highest for low rectangularity and high within-row evenness (Fig. 2). Within-row evenness generally had a stronger effect than rectangularity. Higher *CV* produced a lower predicted yield. For a given *CV*, the effect by varying the rectangularity seems to be less important. The highest predicted yields are achieved for low *CV*s (<0.4) and rectangularity between 0.5 and 4.0.

The shape correction factor becomes important at high values of rectangularity (Fig. 3). This is reasonable because for high values of q it can be assumed that even for crop plant with high plasticity, the available area in a very elongated polygon can only be utilized at some extra cost to the plant. We know of no published research that has investigated this effect, so our assumptions here must be considered a first approximation. The result is very sensitive to the values of the correction parameters in equation (6).

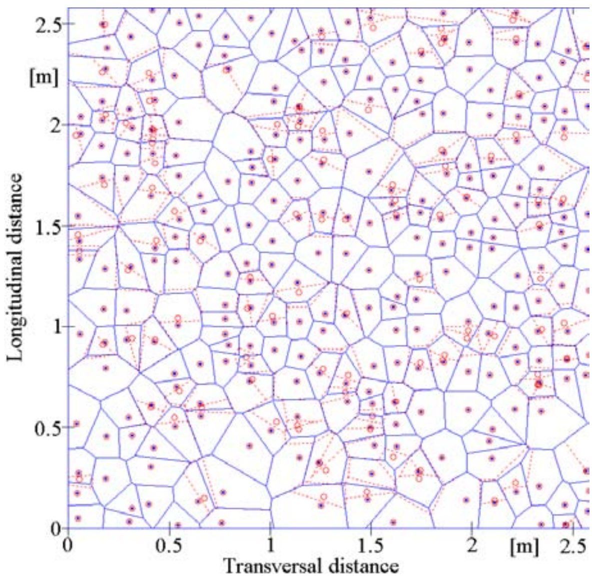

Figure 1. Example of a simulated canola crop spatial pattern. Voronoi tessellations describe the spatial distribution of seeds at sowing date (dashed red) and plants at harvesting time (solid blue). State-of-the-art of canola cultivation today: CV=1.0, rectangularity q=0.86 (row width 0.12 m and mean spacing 0.139 m), seed density 60 m^{-2} and harvest density 40 m^{-2}

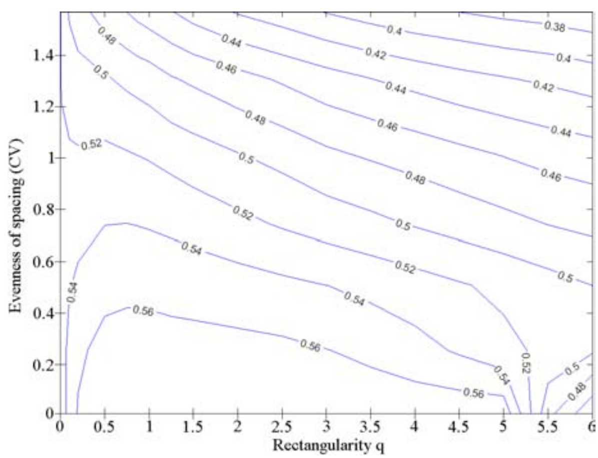

Figure 2. Predicted area yield dry matter [kg m^{-2}] versus CV and q based solely on polygon area

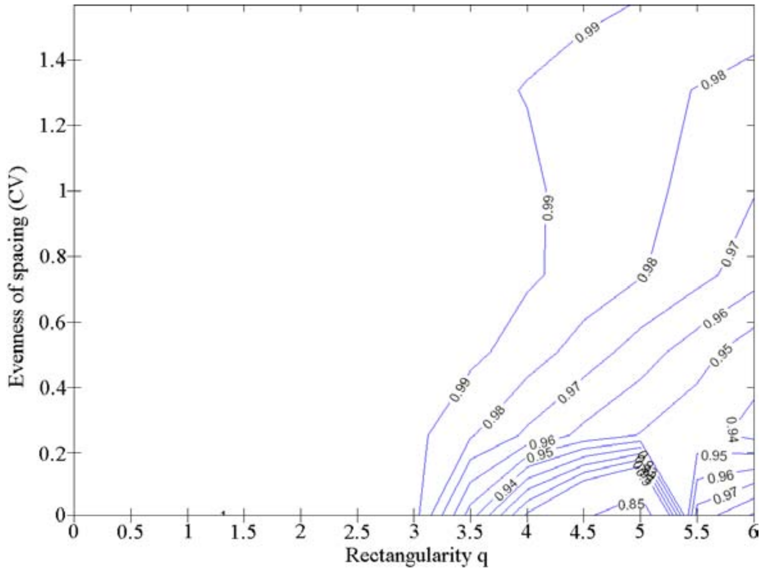

Figure 3. Mean effective shape correction factors versus CV and q

The eccentricity correction becomes important for high values of *CV* and low values of rectangularity (Fig. 4). This is because high values for *q* result in patterns of very elongated polygons with high centricity of plant positions and are almost independent of the within-row *CV*. The highest probability for eccentrically-positioned plants within polygons are for aggregated distributions (high *CV*s and low rectangularity). Again, this potential effect has not been investigated. Not surprisingly, the result depends very much on the settings of the values for the correction parameters in equation (7).

When the shape and eccentricity corrections to the polygons are included, the ranges of *CV* and *q* that produce the maximum yield are reduced, and yield decreases more steeply as the pattern deviates from uniformity (Fig. 5). Typical current canola sowing patterns from conventional grain seeders equipped with bulk metering, have a random plant within-row spacing (CV=1.0) and a rectangularity of around 0.86 (row width 0.12 m, mean spacing within the row of 0.139 m for a density of 60 m^{-2}). According to our simulations, this technology will produce approximately 5.0 t ha^{-1} under the conditions described by Hühn (2001).

Within-row evenness had a strong effect on yield in our simulations, with increasing *CV* producing lower yields. There was also a strong effect of rectangularity. After yield corrections of individual plant for shape, eccentricity and mortality, the highest yields are achievable for rectangularity of between 0.5 and 3.0.

Our results suggest that a promising way to increase the canola yield would be to use precision seeding, which would give a more even plant spacing (CV<0.5). Precision seeding would give a sowing pattern with q=1 and CV=0.5, which would increase yield by 10 % according to our model.

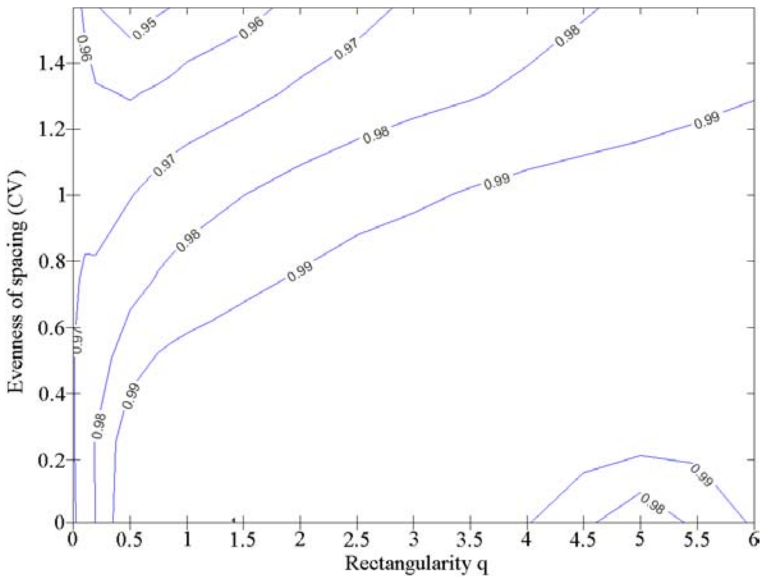

Figure 4. Mean effective eccentricity correction factors versus CV and q

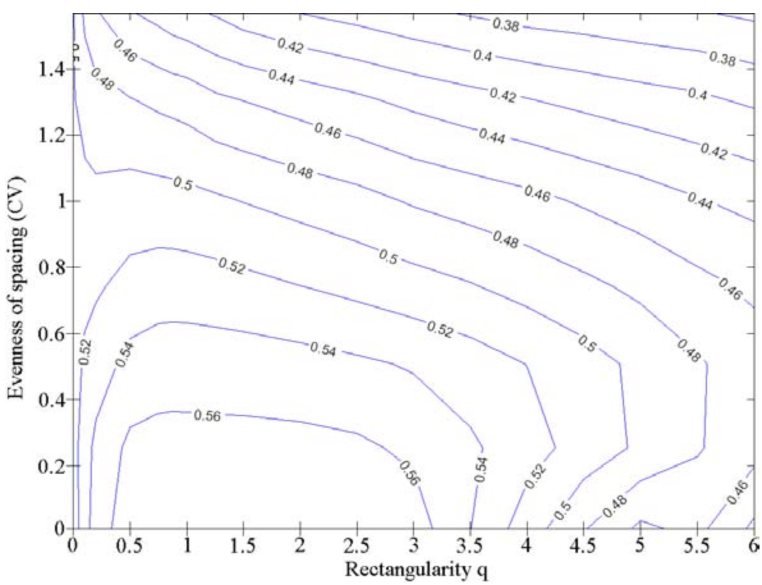

Figure 5. Predicted area yield dry matter [kg m^{-2}] versus CV and q with polygon shape and eccentricity correction

Conclusions

- The *CV* of within-row plant spacing and rectangularity are the main parameters defining crop sowing patterns.
- We can model the effect of these parameters on the 2-dimensional spatial pattern using area, shape and position of crop plant within Voronoi polygons.
- Using published data on canola yield, we can predict the effects of these parameters on yield.
- There is potential for increased yield with improved seeding technology.
- Field experiments with variation in sowing pattern are needed to validate the conclusions presented here.

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References

Bribiesca E. 1997. Measuring 2-D shape compactness using the contact perimeter. Computers & Mathematics with Applications **33** (11) 1-9

Devroye L. 1986. Non-uniform random variate generation. 1st edition. Springer, New York, USA, ISBN 0-387-96305-7

Diggle P.J. 2003. Statistical Analysis of Spatial Point Patterns. Oxford University Press, Oxford, UK

Geisler G., Stoy A. 1987. Untersuchungen zum Einfluss der Bestandesdichte auf das Ertragspotential von Rapspflanzen (Investigations about the influence of crop density on yield potential of canola). Journal of Agronomy and Crop Science **159** (4) 232-240

Griepentrog H.W. 1992. Bewertung von Längsverteilungen bei Einzelkornsämaschinen (Evaluation of longitudinal distribution of precision seeders). Landtechnik **47** (3) 123-125

Griepentrog H.W. 1995. Längsverteilung von Sämaschinen und ihre Wirkung auf Standfläche und Ertrag bei Raps (Longitudinal distribution of seed drills and the influence on crop stand area and yield for canola). Agrartechnische Forschung **1** (2) 129-136

Griepentrog H.W., Olsen J.M., Weiner J. 2009. The Influence of Row Width and Seed Spacing on Uniformity of Plant Spatial Distributions. In: Proceedings International Conference on Agricultural Engineering (AgEng2009) - Innovations to meet future challenges, 6.11.2009 Hanover, Germany, VDI-Verlag, Dusseldorf, Germany, pp. 265-270, VDI-Berichte Nr. 2060

Heege H.J. 1993. Seeding methods performance for cereals, rape and beans. Transactions of the ASAE **36** (3) 653-661

Heege H.J., Billot J.F. 1999. Seeders and Planters. In: CIGR Handbook of Agricultural Engineering, Chap. 1.3, pp. 217-240. ASAE, St. Joseph, USA

Hühn M. 2001. Effects of non-regular spatial distribution of plants on yield per area - a theoretical approach with applications to winter oilseed rape (Brassica napus L.). Journal of Agronomy and Crop Science **187** (4) 241-250

Kristensen L., Olsen J.M., Weiner J., Griepentrog H.W., Norremark M. 2006. Describing the spatial pattern of crop plants with special reference to crop-weed competition studies. Field Crops Research **96** (2-3) 207-215

Mead R. 1966. A relationship between individual plant spacing and yield. Annals of Botany **30** (2) 301-309

Mithen R., Harper J.L., Weiner J. 1984. Growth and mortality of individual plants as a function of "available area". Oecologia **62** 57-60

Panning J.W., Kocher M.F., Smith J.A., Kachman S.D. 2000. Laboratory and field testing of seed spacing uniformity for sugarbeet planters. Applied Engineering in Agriculture **16** (1) 7-13

Pasternak H., Peiper U.M., Putter J. 1987. A method of evaluating seeding uniformity. Canadian Agricultural Engineering **29** (1) 35-37

Steffen R., Wolff R., Iltis R., Albers M., Becker D.S. 1999. Effect of Two Seed Treatment Coatings on Corn Planter Seeding Rate and Monitor Accuracy. Applied Engineering in Agriculture **15** (6) 605-608

Stoll P. & Bergius E. 2005. Pattern and process: competition causes regular spacing of individuals within plant populations. Journal of Ecology, 93, 395-403

Vandermeer J. 1984. Plant competition and the yield-density relationship. Journal of Theoretical Biology **109** (3) 393-399

Weiner J., Griepentrog H.W., Kristensen L. 2001. Suppression of weeds by spring wheat *Triticum aestivum* increases with crop density and spatial uniformity. Journal of Applied Ecology **38** 784-790