OPTIMIZING VEGETABLE STRIP INTERCROPPING SYSTEMS FOR APPLICATION IN THE NORTH CHINA PLAIN – ECOLOGICAL RESEARCH FOR A SHIFTING ECONOMY

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Abstract

The simultaneous cultivation of different crops on the same field has been an important aspect of agriculture for millennia, but the modern industrial system, with a heavy focus on inputs and monocultures, has marginalized it. The North China Plain (NCP) in eastern Asia produces some one fifth of China's food, and this marginalization is being witnessed there on a massive scale today. Due to labor migration for higher wages to urban areas like Beijing, traditional intercropping in the NCP is endangered, as it requires significant manual labor. In this study, we experiment with varying maize cultivars, as well as different strip width arrangements in a monocrop setup, in order to theoretically study how the rows of maize plants would modify the microclimate of a neighboring vegetable crop. Locally important vegetable crops in the NCP include bush bean (*Phaseolus vulgaris* L.) and Chinese cabbage (*Brassica campestris* L. ssp. *pekinensis*). Knowing the physiological adaptations of the neighboring plant to a modified microclimate from the growth of the maize plants allows us to model the vegetable plant response in terms of biomass yields. We find that the Amagrano cultivar has the best performance for a number of parameters, but that Amagrano also has the tallest plant height and the second-highest leaf area index (LAI), meaning it would transmit comparatively less radiation to a neighboring crop. Researchers need to recognize that the strong above-ground competition for light in strip-intercropping systems must be minimized by using maize cultivars with different morphologies (e.g. reduced plant height, more erect leaves) and by reducing the maize strip width. We conclude that the use of prolific maize hybrid varieties should be considered when designing strip intercropping systems to increase the crop yield in the border rows, especially in high solar radiation conditions like the NCP. Improvement of plant growth modeling is essential to better understand temporal and spatial plant competition, thereby optimizing the systems. Regionalizing the suitability of strip intercropping for China, Germany and possible other regions with varied weather, soil, and especially irrigation conditions is also essential for future agricultural planning.

INTRODUCTION

Intercropping, growing two or more crops in association with one another, has been an important management technique throughout the history of agriculture (Vandermeer 1, 1989), yet it has become marginalized by the modern industrial system. With new calls for reform of the global agricultural system, it is essential that renewed study of this traditional technique be undertaken. The purpose of the present study is to empirically evaluate how plant growth and production are influenced spatially and temporally by row intercropping of maize and various vegetables.

Gaining this data is essential for improving existing computer crop models such as the Decision Support System for Agrotechnology Transfer (DSSAT Foundation, 2011) software (version 4.5) to simulate strip-intercropping systems, thereby helping to evaluate different strip-intercropping agricultural systems for farmers in the North China Plain (NCP). The NCP is the largest alluvial floodplain in eastern Asia, covering some 300,000 km^2, and it produces some one-fifth of China's food (Müller et al. 2009; Feike et al. 2010c, 272). At 1.34 billion people, China is the world's most populous nation (U.S. Central Intelligence Agency 2011). With an escalating population comes the imminent need to achieve a more resilient food system in China.

Mixed intercropping has been practiced in China for millennia (Chandler 1994; Li et al. 2001; Knörzer et al. 2009). Although resource degradation must be addressed, there nevertheless remains the need to maintain the high levels of food production. Intercropping could help resolve this apparent contradiction, as it frequently generates higher yields per land area than monocropped areas (Jolliffe 1997; Zhang and Li 2003) due to better utilization of water (Walker and Ogindo 2003; Müller et al. 2009), nutrients (Li et al. 2001; Müller et al. 2009), and available solar radiation (Keating and Carberry 1993; Tsubo et al. 2001; Alene and Hassan 2003; Carrubba et al. 2008; Feike et al. 2010a). For future agricultural development, it is important to consider not just the sheer agricultural output of a system, but efficiencies over generations (Vandermeer 2011). Intercropping has the potential to reduce chemical inputs, better regulate soil erosion, and reduce nutrient leaching in soil solution, if the system is designed well (Wahua 1985; Whitmore and Schroeder 2007; Müller et al. 2009). Agricultural monocropping in the NCP needs to be revised in the face of environmental sustainability, income security for farmers, and nutritional diversity in rural NCP areas (Knörzer et al. 2009).

Figure 1. Political map of China. *Source*: U.S. Central Intelligence Agency. The World Factbook. 2011. *East & Southeast Asia: China*. Washington, D.C.

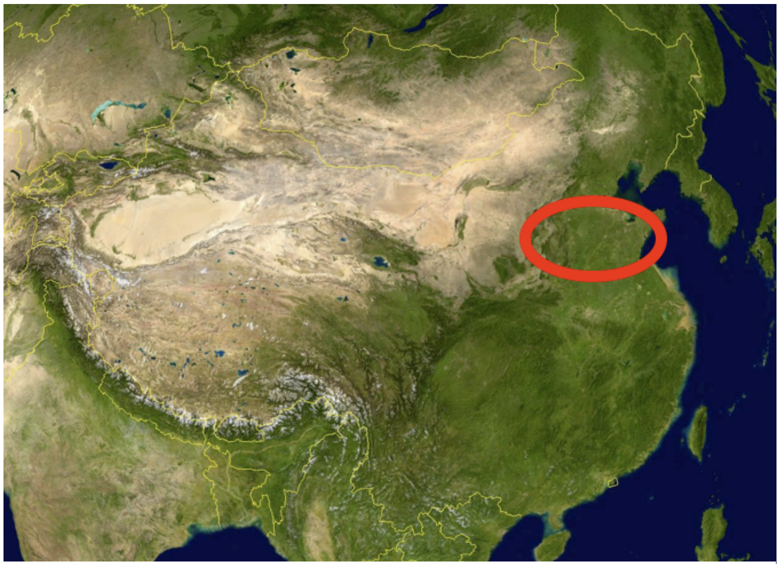


Figure 2. Satellite image of East Asia with the NCP highlighted with a red oval. Notice the limited fertile land area for additional agricultural expansion in the region; the western region is mountainous and largely impractical for agricultural use. *Source*: NASA. NASA's Worldwind Program. 2009. *China Satellite Photo*. Washington, D.C.

The NCP is characterized as a continental monsoon climate with average temperatures ranging from less than 0˚C in January to 27˚C between June and August (figures 1,2) (Feike et al. 2010c, 273). Annual rainfall in the region falls between 300 and 700 mm, with the 70% of precipitation falling in the summer months (Müller et al. 2009). Farmers widely use irrigation to extend the growing season between October and April (Müller et al. 2009; Feike et al. 2010c, 273), but this leads to water and land resource degradation (Dazhong et al. 1992). These climatic data were collected at The Quzhou Experimental Station, located in the Handan city region, Hebei province, at 36˚52' N latitude, 115˚0' E longitude. Common crops in the NCP include wheat, maize, cotton, and fruits and vegetables (Feike et al. 2010c, 273).

By testing parameters such as species and cultivar selection for intercropping with maize, as well as strip width arrangements in a monocrop setup, we can theoretically study how the rows of maize plants would modify the microclimate of a neighboring vegetable crop. Locally important vegetable crops in the NCP include bush bean (*Phaseolus vulgaris* L.) and Chinese cabbage (*Brassica campestris* L. ssp. *pekinensis*). Knowing the physiological adaptations of the neighboring plant to a modified microclimate from the growth of the maize plants allows us to model the vegetable plant response in terms of biomass yields.

The motivation for this study is based on the trend of increasing rural-urban migration from the NCP to nearby cities like the capital, Beijing, due to higher urban wages; this leads to a scarce agricultural labor market in rural areas (Feike et al. 2010b, 2149; Feike et al. 2010c, 272; Munz et al. 2011, 268). In light of severe land and water resource degradation in the NCP (Dazhong et al. 1992), there is an imminent need for agricultural systems that are 1) more sustainable than existing systems and 2) sufficiently productive in terms of crop yield. In the past decade, vegetable production was extended largely in the NCP, further degrading environmental resources, due to high inputs of water and nutrients (fertilizers) associated with intensive vegetable systems (Feike et al. 2010c, 273). Agricultural intercropping can increase water and fertilizer use efficiency (Walker and Ogindo 2003), improve land use efficiency (Fike et al.

2010b, 2150), and reduce pest pressure in the system (Feike et al. 2010b, 2149; Feike et al. 2010c, 273). There are few international research programs established to understand and address NCP food security (Knörzer et al. 2009), and serious consideration must be placed on the current state of the Chinese food system.

The land area devoted to intercropping in China is the largest in the world, with between 28 and 34 million ha of annually sown area, and only about 16% of Chinese land area is arable (Knörzer et al. 2009). Expanding agricultural land area is a tremendous challenge, as existing NCP land is severely degraded, due to an overuse of water and fertilizer resources, creating substantial groundwater depletion and eutrophication of water resources (Dazhong et al. 1992; Whitmore and Schröder 2007; Feike et al. 2010c, 273). Further, Chinese farmers are unable to increase the size of their farms, due to restricted land-use rights (Knörzer et al. 2009). The notions of intensifying agricultural production while minimizing environmental risk are seemingly mutually exclusive; intensive systems generally require higher inputs of water and nitrogen fertilizer, which aggravate – not alleviate – environmental degradation (Dazhong et al. 1992).

Part of the solution to combatting environmental degradation while adjusting to the NCP socioeconomic situation might result from the improvement of existing Chinese intercropping systems (e.g. maize-wheat, maize-chili, cotton-onion), and/or the development of new strip-intercropping systems. Strip intercropping means simultaneously cultivating two or more crops in different strips, wide enough to allow for independent cultivation, but narrow enough so that the crops can interact biologically (Vandermeer 1989). Strip intercropping agricultural systems with a component of mechanization have the potential to compensate for labor scarcity. Mechanization allows farmers to maintain high levels of crop yields with comparatively less manual labor than has historically been possible. Tractors and other agricultural machinery allow fewer farmers to produce the same amount of food. Strip intercropping offers similar benefits of traditional intercropping systems and allows for mechanization, unlike traditional Chinese systems. This study focuses on testing the effects of various maize plant arrangement scenarios on maize growth grown in strips and the modification of the microclimate of a neighboring plant by the maize strips. The study was conducted in Stuttgart, Germany, and it is intended to guide agricultural practices in the NCP.

Study Objectives and Hypotheses

We hope to determine a quantitative relationship between maize strip width, maize cultivar, and intercepted solar radiation to a theoretical neighboring crop. The study is conducted in a monocrop fashion in which all plants are maize. With these relationships, we hope to identify the most important parameters for the optimal choice of strip width (number of maize rows) and maize cultivar (plant height, leaf angle, leaf area). The overall system productivity depends largely on the quantity of transmitted radiation to a neighboring crop (due to aboveground competition for light).

Second, we aim to provide data on plant yield parameters in a monocrop setup to aid further studies regarding vegetable strip intercropping. We hope to gain a more refined perspective of how different maize cultivars perform across a monocrop strip (border rows 1,2,9,10 versus middle rows 5,6). We ask if the border rows exhibit reduced height growth, due to the less intraspecific light competition. Does less light competition in the border rows lead to increased yields? If so, why? For this purpose, yield components (kernel number, kernel weight and number of cobs per plant) will be compared to determine the growth stage at which plant competitive effects exist (Lesoing and Francis 1999). We will interpret the monocrop results considering a theoretical strip intercropping system (Lesoing and Francis 1999; Andrade et al. 2000). The land equivalent ratio criterion is often used to compare the relative effectiveness of intercropping versus monocropping (Vandermeer 75, 2011). Innis (1997) found that, in nearly all international studies using the LER criterion, intercropped species overyielded their monocropped counterparts. We will only compare the border rows with the middle rows in this study, though, because we can only compare the individual maize rows. The main hypothesis behind the experiment is that intercropping of Chinese cabbage and bush bean with maize can significantly increase land use efficiency, compared to monocropping of the plants individually.

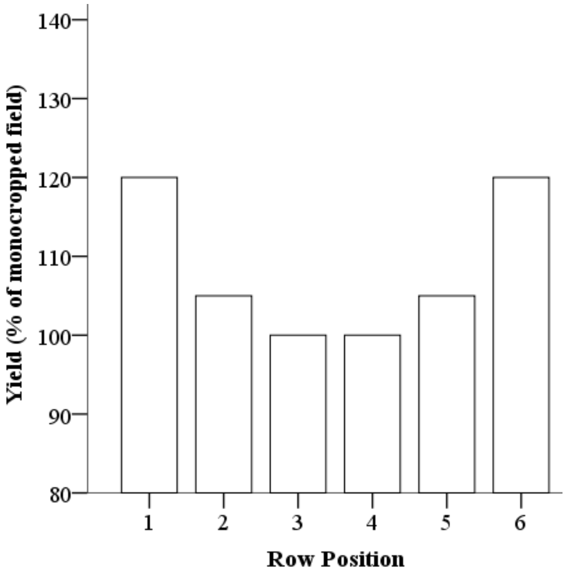


Figure 3. The effect of maize row position on final yield for a six-row strip. Data are expressed as a percent of yields generally observed with monocrop maize arrangements. *Source:* Data from Cruse, Richard M. 2008. Strip Intercropping: A CRP Conversion Option | Conservation Reserve Program: Issues and Options. Iowa State University Extension and Outreach. https://store.extension.iastate.edu/ItemDetail.aspx?ProductID=1103 (Accessed April 12, 2012), figure 1.

Another component to this study is modeling maize plant growth (focusing on plant height increment) and its impact on the radiation regime for the adjacent vegetable crop on an hourly scale with R software (R Foundation for Statistical Computing, 2011) using the black box approach. The black box approach involved assuming the maize plant height is the height of a black wall, meaning no radiation is transmitted through the strip (Pronk et al. 2003). We used an average height across the strip to see if only the height of the first border row has a significant influence, especially for higher sun elevation settings. Because of the complex interactions inherent in the intercropping system, modeling is a central component of the research; we can then better understand the various interactions and attempt to optimize the balance between temporal and spatial resource demand and usage of the crops through computational modeling. Another component might be to use weather data from Ihinger Hof experimental station to correlate with plant height, specifically growing degree days (base temperature 8˚C), but this was not included in in the study. Finally, we determined shadow and day length using R, meaning the time of the day that crops are not shaded, depending on location (latitude/longitude), maize plant height, and distance to the maize strip.

Our hypotheses in the study are as follows. We predict a greater crop yield for maize in the first two border rows in a strip setup (figure 3) (Cruse 2008, 2) and decreased yield for a theoretical neighboring crop due to the shading effects of maize. Previous studies have found that the first two rows of Chinese cabbage and the first row of bush bean experience decreased yields (Munz et al. 2011, 269; Müller et al. 2009, 2). Second, we presume that plant height is quantitatively the most important parameter that determines the amount of transmitted radiation to a neighboring crop, assuming leaf area index (LAI) does not differ much between cultivars and leaf angle has a minor effect.

We presume there will be no change in the amount of transmitted radiation to a theoretical neighboring vegetable crop above a certain strip width (assume > 4 rows) (Munz et al. 2011, 269). We expect an increasing final plant height of maize plants per row with additional rows, and we infer that the maize intercepts more light next to the first row of a neighboring crop, meaning more solar radiation is available further from the maize (Carena and Cross 2003). We will also investigate the final yield parameters for the maize cultivars, in order to suggest arrangements for farmers in the NCP. This is important because, if a certain maize cultivar is deemed suitable for a particular arrangement in the NCP (e.g. transmits adequate radiation to the neighboring crop), it must also have a high yield. Otherwise, the crop combinations would not be appropriate for farmers in the NCP.

My research mentor in Germany was Sebastian Munz, a PhD student at the Institute of Crop Science at the University of Hohenheim. The research project is part of Sebastian's PhD dissertation research, "Optimization of Intercropping Systems in the North China Plain: Field research and Modeling." Parallel experiments were conducted in the NCP through a joint partnership with the China Agricultural University, in Beijing. The research project in Germany is part of the so-called "International Research Training Group" (IRTG) on sustainable resource use in North China, which is a team of international PhD students at the University of Hohenheim from five countries. The IRTG was established in 2004, and the program has funding through 2013; it was established through the Deutsche Forschungs-gemeinschaft (DFG) and the Chinese Ministry of Education at the University of Hohenheim, and it partners with The China Agricultural University, in Beijing.

The results from the German experiments are translatable to Chinese farmers due to the DSSAT software, a computer-modeling program that standardizes results for varied growing conditions. At its current state, DSSAT software is limited to agricultural monocropping applications. Due to the myriad of potential crop combinations, as well as the available spatial and temporal arrangements, there is tremendous potential to optimize existing Chinese intercropping systems. Field experiments that evaluate every possible arrangement and crop combination would be unrealistically time and labor-intensive, so computer modeling is seen as a pivotal tool to optimize these systems. This project fits within the broader aim of Sebastian's PhD thesis, which is to develop a strip-intercropping model to test various crop arrangements, fertilization levels, and irrigation treatments, in order to test the suitability and optimize strip-intercropping systems under various conditions (weather and soil conditions).

METHODS

Study Site

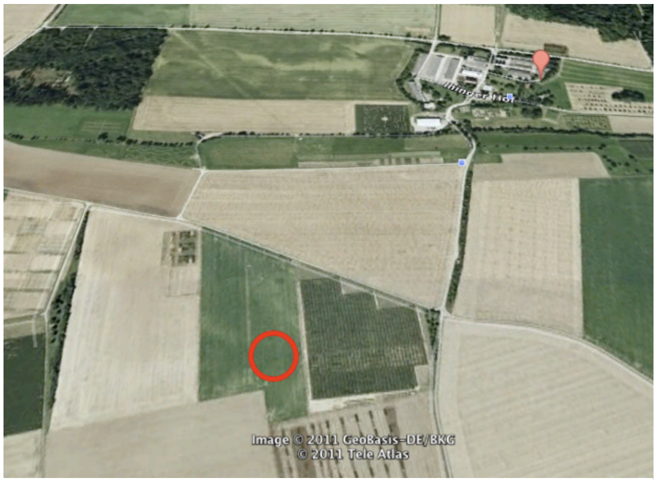


Figure 4. Ihinger Hof experimental station in Renningen, Germany. Research site is indicated with a red circle. *Source*: Google Maps. http://maps.google.com/ (accessed December 1, 2011).

Figure 5. Political map of Germany. Renningen is indicated with a circle. *Source:* U.S Central Intelligence Agency. The World Factbook. 2011. *Europe: Germany*. Washington, D.C.

I traveled to Stuttgart, Germany, from May 15 through August 7 and conducted research at the University of Hohenheim. The study site is located at "Ihinger Hof" experimental field station in the southwestern German city of Renningen (see figures 4,5). Ihinger Hof is located at 48˚45' N latitude, 8˚56' E longitude, and approximately 400 m above sea level (Boehmel et al. 2008). In 2011, Ihinger Hof field station received a total precipitation of 417.8 mm, and the average temperature was 13.39˚C (collected at a height of two m) from the beginning of March through October, which was the total maize growth period. The study site is characterized as a silty-clay-textured Haplic Luvisol with an upper layer of loess. The soil total nitrogen (N_t) and total carbon (C_t) levels of dry soil in spring 2004 were 0.92% to 1.07%, and 0.10% to 0.11% respectively (Boehmel et al. 2008).

Experimental Design and Field Preparation

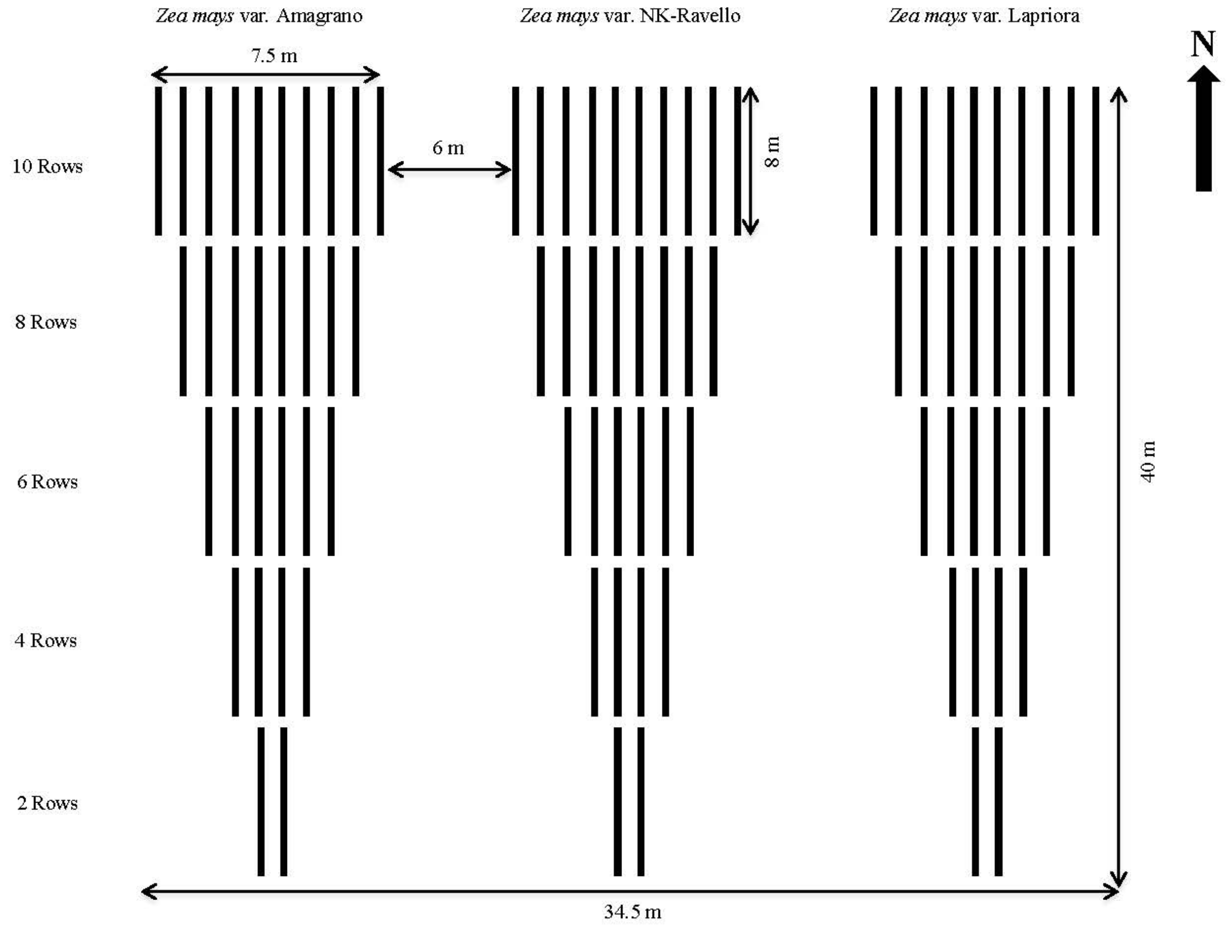


Figure 6. Experimental design. Each treatment represents a maize cultivar. From East – West: Lapriora, NK-Ravello, Amagrano. The experiment is arranged such that each treatment has the same dimensions, but there are no repetitions for each maize cultivar treatment.

The experimental design consisted of growing three different cultivars of maize in crop arrangements that vary with the number of rows per strip (see figure 6). There were three treatments – one for each cultivar – and each one had strips of 2, 4, 6, 8, and 10 maize rows (see figure 6). Because of practical purposes (machine sowing) initially, each plot consisted of one 40 m strip with 10 maize rows. After emergence, we removed the additional maize plants to create the experimental arrangement of strip widths. The cultivars were: Lapriora (KWS SAAT AG, Einbeck, Germany), NK-Ravello (Agromais GmbH, Everswinkel, Germany), and Amagrano

(Syngenta Seeds GmbH, Bad Salzuflen, Germany). Each cultivar has a characteristic morphology, which is important for deciding which vegetable species would be appropriate next to the maize in a strip intercrop setup. Lapriora has a reduced plant height, fast growth, and very early maturation; NK-Ravello has increased plant height and more erect leaves; and Amagrano has a normal shape, meaning Amagrano should be tallest. All cultivars are short season (early maturing) types.

The strips were oriented North-South, which is suitable for high latitudes to exclude shading to a neighboring crop during the greatest solar irradiance at noon. We realize that this experimental design has no controls, and that there are no repetitions for the maize cultivars, but we assumed that the repetitions were representative of how *all* maize cultivars would perform under these conditions. While this may violate fundamental statistical assumptions about the validity of the data, we decided that this experiment would at least provide data on plant yield parameters in a strip cropped maize setup, thereby guiding future studies regarding vegetable strip intercropping.

In order to determine the effects of maize plant shading on an adjacent crop theoretically, we took measurements regarding maize plant growth and solar radiation regime. To record plant growth, we took weekly measurements of plant height, plant width, number of wilt & green leaves, the number of cobs, leaf angle, and leaf area. These measurements also indicated the stage of plant growth (BBCH). The BBCH scale is used to determine the degree of phenological development in a plant species (Lancashire et al. 1991). We also took weekly measurements of photosynthetically-active radiation (PAR). We measured leaf angle distribution on maize plants using a protractor and taking photos of the plants, to be analyzed later using GIMP2 software.

Before establishing the experiment at Ihinger Hof station, the study site underwent a series of preparations. On April 18, 160 kg N*ha^{-1} Urea (46% N) was applied and incorporated with a rotary harrow to a depth of 15 cm. Potassium and Phosphorus were not applied due to a high degree of soil fertility. The three maize cultivars were sown on April 26 with a density of 85,000 seeds*ha^{-1} at a row distance of 75 cm. The herbicide product "MaisTer" was applied to the maize plants on June 16 (6-leaf stage [51 days after sowing]) at a concentration of 1.5 L*ha^{-1} diluted in 340 L*ha^{-1} H_20.

Destructive measurements

Destructive measurements were taken on July 20 and October 18 [85 and 175 days after sowing], respectively. July 20 was the maize silking stage (BBCH 65), taken at 1m^2 intervals (1 row*1.33 m); October 18 was the final harvest date (BBCH 89), taken at 2m^2 intervals (1 row*2.66 m). At silking, total dry matter and LAI were determined. LAI of three plants per 2m^2 sample were measured with a LI-3100 Area Meter (LI-COR Biosciences, Lincoln, Nebraska, USA). At physiological maturity, total dry matter, grain yield, and thousand-kernel weight were determined. Plant samples were dried to constant weight at 70˚C in a Heraeus UT 3 oven incubator (Thermo Fisher Scientific, Waltham, USA).

Figure 7. Indication of selected maize plants (in red) for weekly measurements. Measurements were taken for five plants per row.

The weekly measurements described above were conducted by starting from the strip with two rows. We measured five consecutive plants in the first and second rows. Then, we measured five consecutive plants in the first and second rows in the strips with four rows. For the six, eight, and ten row sections, we measured the first and second rows, as well as the middle rows (third, fourth, and fifth rows, respectively) (see figure 7).

Radiation Measurements

Figures 14 and 15 display the results of the continuous PAR measurements. These measurements could be used to check the shadow length calculations in our computer model (discussed later). The PAR measurements were taken with a PAR/LE Line 30 cm PAR sensor (Solems, S.A., Palaiseau, France), calibrated with a LI-190 SL Quantum Sensor (Li-Cor Environmental Division, Lincoln, Nebraska, USA). Measurements were taken every 10 seconds and logged as an average of 1 minute with a CR23X Micrologger (Campbell Scientific, Inc., Logan, Utah, USA). Measurements were taken on June 28 [63 days after sowing] for Lapriora and June 29 [64 days after sowing] for NK-Ravello and Amagrano. Both days were clear and sunny. The results of the continuous PAR measurement plots were conducted by plotting the results in Excel into a time-series graph. The spreadsheet recorded contained values for PAR measurements within each cultivar at various distances from the maize plants (2 rows 0.5 m; 2 rows, 1 m; 4 rows 0.5 m; 6 rows 0.5 m; 8 rows 0.5 m; 10 rows 0.5 m). The PAR sensors were established to the West in the morning hours (9 am - 1 pm) and to the East in the afternoon (1 pm – 8 pm).

To calculate maize-plant intercepted solar radiation, we also measured PAR in each cultivar with a linear PAR ceptometer (Model AccuPar LP-80, Decagon Devices, Pullman, WA, USA). The measurement protocol for July 4 [69 days after sowing] was taking an open-air PAR value, followed by three to five measurements in the middle rows of maize (5 and 6), followed by a final open-air measurement. The ceptometer could also calculate LAI (see table 3). By pressing enter at the end of the measurement sequence, the ceptometer took the measurements to be a single value by averaging them. This measurement protocol enabled us to calculate intercepted radiation, as well as LAI. On July 5; BBCH 16 [70 days after sowing], we also took open-air PAR values away from crops, then five values adjacent to the maize plants (60, 110, 260 cm distances, denoted by blue markers), followed by another open-air value at end of the row. We pressed enter after each measurement in this case, meaning each measurement was marked as a separate value in the ceptometer.

Shadow length model

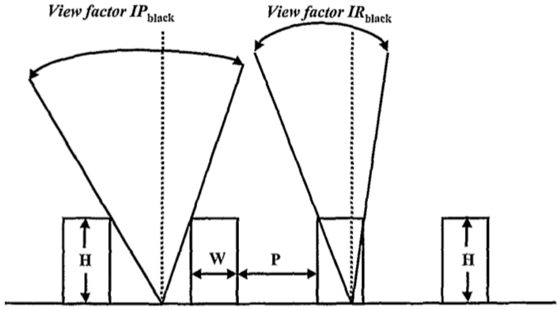


Figure 8. Sky boundaries visible from various points in the intercropping setup described by Pronk et al. 2003. To the left is the inter-row space (view factor IP_{black}), and the right displays the view from inside a plant row with infinite LAI. H = plant height, W = plant row width, and P = bare path width. *Source:* Pronk, A. A., et al. "A Simple Method to Estimate Radiation Interception by Nursery Stock Conifers: A Case Study of Eastern White Cedar." *NJAS - Wageningen Journal of Life Sciences* 51.3 (2003): 283. Print.

We developed a computer model using R computer software to calculate the shadow length that maize plants cast on a theoretical neighboring crop; the model can be used for different locations globally (see Appendix A and figure 17). The model is based on one that Pronk et al. (2003) proposed, a simple approach that displays when a neighboring crop is- or is not shaded, depending on: 1) time and location, 2) maize plant height, and 3) distance to the neighboring crop (see figures 8,9,10). The model was adapted from an online R forum (Stack Overflow, posted January 3, 2012). That code, in turn, was adopted from various sources (Walraven 1978; Michalsky 1988, 1989; Spencer 1989). The model could integrate the height of the neighboring crop if an additional component were added; the higher a neighboring crop grows, the earlier it receives full incoming PAR. In its current version, the model contains the distances of the different rows in Sebastian's strip intercropping system experiment, meaning the final output gets reduced to those distances.

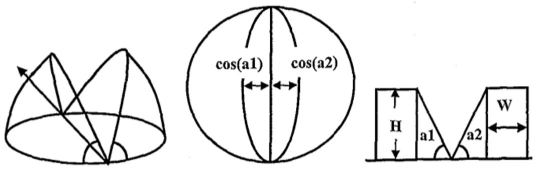


Figure 9. The vertical projection of the "view factor" path. H = plant height, W = plant row width, and a1 and a2 are the inclinations of solar incident rays in the Earth's normal polar coordinate system. The arrow on the left-most diagram points in the direction of the plant row. *Source:* Pronk, A. A., et al. "A Simple Method to Estimate Radiation Interception by Nursery Stock Conifers: A Case Study of Eastern White Cedar." *NJAS - Wageningen Journal of Life Sciences* 51.3 (2003): 283. Print.

Traditional row crop systems tend to reduce intercepted canopy radiation because the leaves strongly shade one another and most of the incoming radiation falls onto the soil surface (Pronk et al. 2003, 281). Another assumption is that direct or diffuse solar radiation does not affect the average fraction of radiation intercepted; isotropy, or homogeneous radiance from the entire sky, is an often-used assumption (Goudriann 1977, 1988). This becomes particularly important during cloudy days, when it is challenging to take continuous PAR measurements with consistent sky conditions. The Pronk et al. model can calculate the fraction of transmitted radiation by first considering the theoretical case of a so-called "black" row, where there is an infinite LAI value. This can be calculated with a known path width, plant row width, and plant row height. The so-called "view factor" of the sky is the solar radiation level at a horizontal surface element of the path, divided by the radiation level above the canopy.

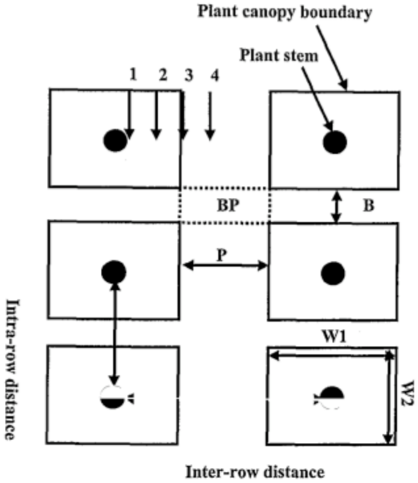


Figure 10. A possible experimental setup for measuring radiation interception, as described in Pronk et al. 2003. P = bare path width, B = bare intra-row area, BP = bare area between B and P, W1 = plant width across the row, W2 = plant width in the plant row. 1-4 = points where the radiation was measured. *Source:* Pronk, A. A., et al. "A Simple Method to Estimate Radiation Interception by Nursery Stock Conifers: A Case Study of Eastern White Cedar." *NJAS - Wageningen Journal of Life Sciences* 51.3 (2003): 285. Print.

The case of non-infinite LAI is when the plant row transmits radiation (no "black" row), which increases the level of IP_{black}.

Data Analyses

The data were analyzed with a combination of IBM SPSS Statistics19 and Microsoft Excel 2010 programs. Average maize final plant height at harvest was calculated in SPSS using an Excel dataset containing nine weekly measurements of maize plant growth (May 27 through July 25) at Ihinger Hof station [31 and 90 days after sowing, respectively]. The measurements were taken from ground-level to the tallest part of the maize plants. July 25 marks the period around which the maize plants cease stem elongation and begin to devote energy resources to silking and tasseling, which help the plant prepare for grain filling (BBCH 65).

The other statistical analyses relied on a dataset that was compiled after the final maize harvest (October 18; BBCH 89 [175 days after sowing]), which contained eighteen $2m^2$ samples (six from each cultivar) and various measures of maize yield. The maize plants in border rows (1,2,9,10) and middle rows (5,6) were included in the final destructive measurement (see figure 11). The yield measures included the number of cobs per plant, the number of cobs per $2m^2$ area, the total dry matter of cobs ($g*2m^{-2}$ area), thousand kernel weight, kernel number per plant, and dry matter of kernels ($g*plant^{-1}$; $g*2m^{-2}$ area; $kg*ha^{-1}$).

Figure 11. Indication of selected maize plants (in red) for second destructive measurement. Yield measurements were taken for $2m^2$ samples per row.

To determine the differences between maize yield in border rows and middle rows between cultivars, I ran a series of two-way ANOVAs in SPSS. I assigned the fixed factors to be

"Cultivar" and "Border_Middle," and I changed the dependent variable (a parameter for final maize yield) for each repetition. I assigned "0" to the middle rows and "1" to the border rows; there were six cases for middle row values and twelve cases for border rows.

To assess the reliability of the data, I ran a series of Tukey nonadditivity tests in SPSS. I performed eight repetitions of the test by changing the items under consideration for each one to include each of the yield measures listed above. In each repetition, there were three valid cases under consideration and six items, or one value per row number (1,2,5,6,9,10). I chose to run the Tukey nonadditivity test because my dataset had only one observation per cell in at least two groups, meaning there can be no within-cell variation; no direct estimate of experimental error could be calculated (Winer 1971, 394). If the strictly additive model is appropriate in the Tukey test (no interaction effects), then the experimental error can be used as an estimate (Winer 1971, 473-475). I set the significance level to α=0.25 to decrease the probability of having a type 2 error (a low type 2 error means there is a low probability of using the additive model when it is actually inappropriate).

RESULTS

Plant height was calculated for each cultivar on July 25: BBCH 65 [90 days after sowing], which can be considered the final plant height (see figure 12b). From tallest to shortest were Amagrano, NK-Ravello, and Lapriora. These data reflect the total aggregate average height of maize plants in *every* row for each treatment. Lapriora develops the fastest, so it has a higher plant height than NK-Ravello at an earlier stage (Figure 12a), but its final height is lowest at the silking stage, when the maize plants cease stem elongation (Figure 12b). Figure 13 indicates the same pattern for average cultivar height differences, as well as an overall trend of increasing final average plant height for maize plants with an increasing number of rows. While this trend does not hold for NK-Ravello in rows eight and ten, as well as Amagrano in row ten, the general pattern of increasing plant height with additional rows is consistent. Increasing plant density has been correlated with increased height, in terms of varying intraspecific competition for light (Carena and Cross 2003).

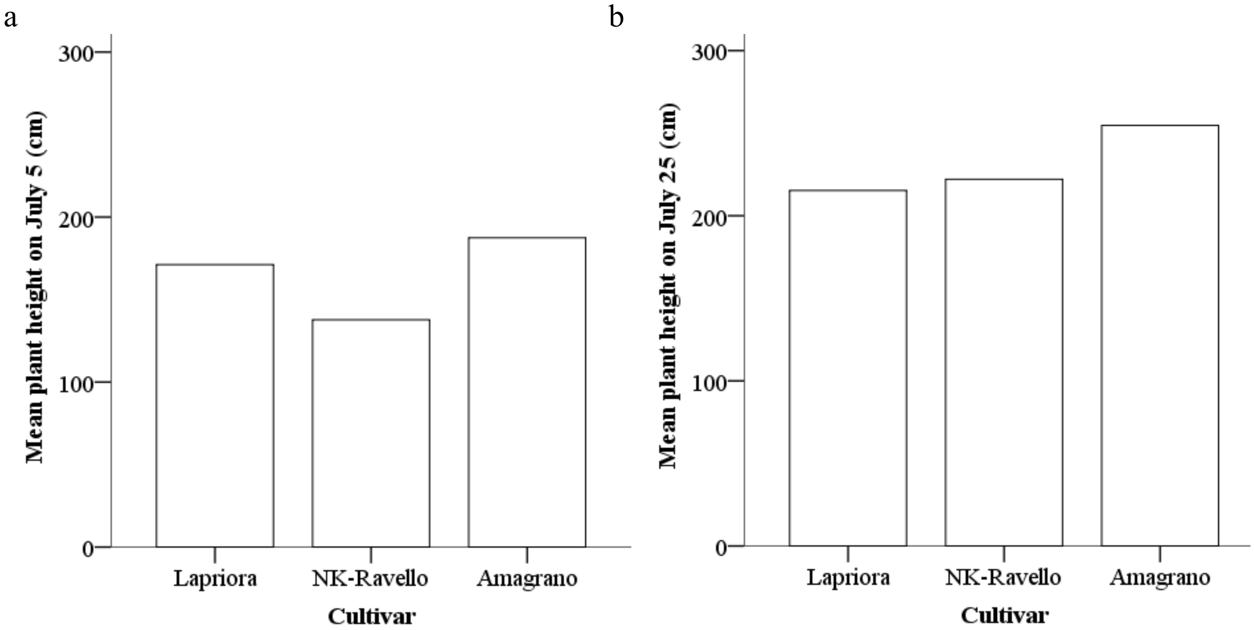


Figure 12. Average maize final plant height at two stages of maize development: (a) July 5 BBCH 16 [70 days after sowing], and (b) July 25 (silking) BBCH 65 [90 days after sowing].

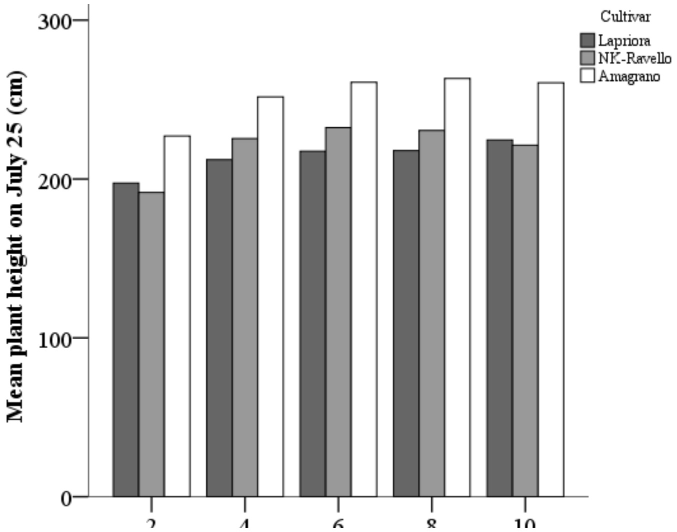
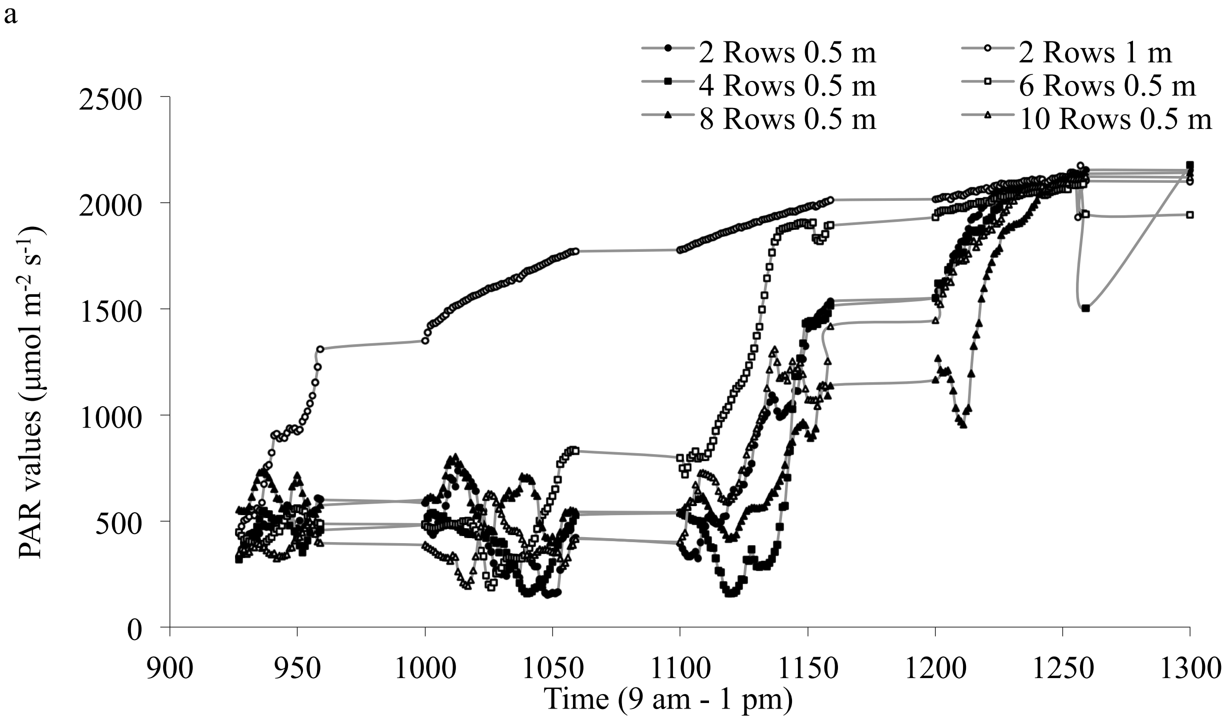


Figure 13. Average maize final plant height at silking (July 25: BBCH 65) [90 days after sowing] by row number.

The results from the continuous PAR measurements are included below. For every case (see figures 14,15), the incoming solar radiation values increased with time until midday (1 pm), and they decreased after midday until the end of the recording period (8 pm). In each measurement, the highest PAR reading was recorded for the 2 rows, 1 m treatment, meaning these treatments recorded the highest transmitted incoming solar radiation. The second highest transmitted PAR was observed for Lapriora in the 6 rows, 0.5 m treatment in both the morning and afternoon calculations (figures 14a,b); NK-Ravello had the second highest transmitted PAR in the 2 rows, 0.5 m treatment (figure 15a); Amagrano was mixed and unclear, with either the 8 rows, 0.5 m, or the 2 rows, 0.5 m treatments exhibiting the second highest transmitted PAR values (figure 15b).

The lowest transmitted PAR values were observed in the 4 rows, 0.5 m and 8 rows, 0.5 m treatments for Lapriora in the morning (figure 14a), and the 8 rows, 0.5 m treatment during the afternoon (figure 14b). For NK-Ravello, the lowest PAR values were observed in the 4 and 8 rows treatments at a 0.5 m distance (figure 15a). The lowest recorded transmitted PAR values for Amagrano were observed in the 8 rows, 0.5 m treatment (figure 15b). These mixed results are unclear, as we would expect the eight and ten row treatments to intercept the greatest amount of incoming solar radiation for *all treatments*, as they contain more individual plants, hence a denser strip.



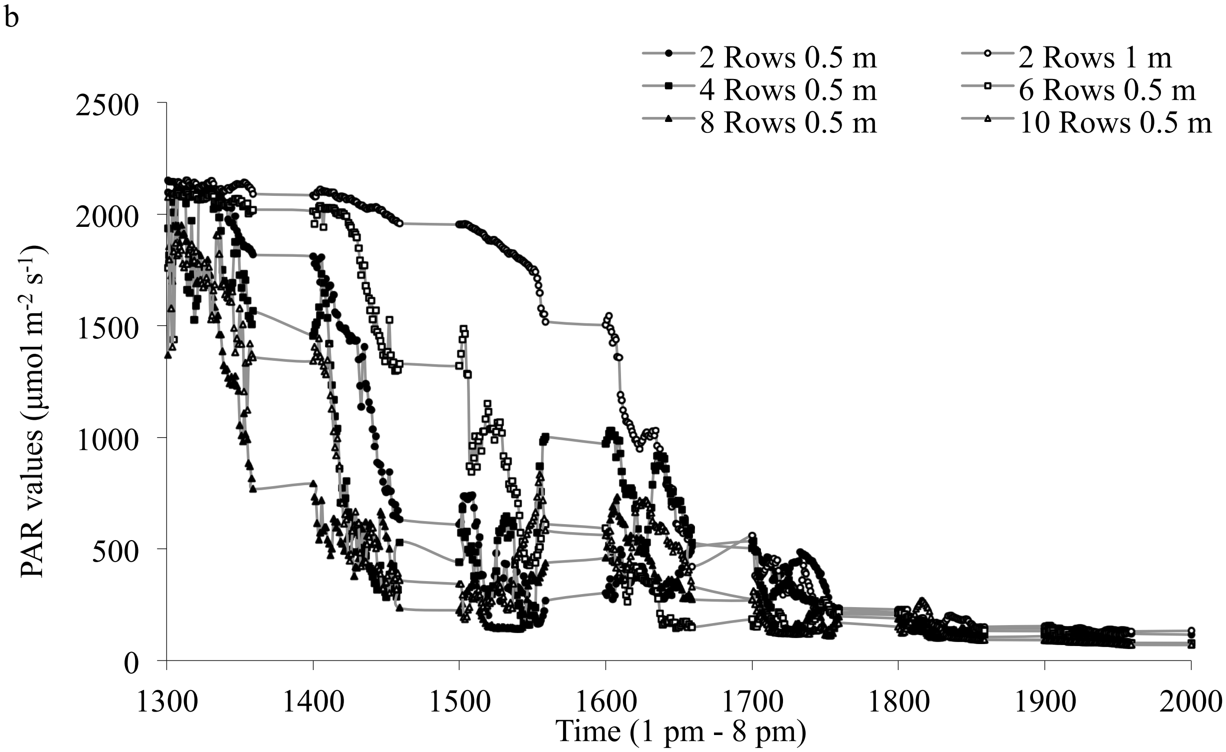


Figure 14. (a) Lapriora continuous PAR measurement from 9 am until 1 pm on June 28 [63 days after sowing] and (b) Lapriora continuous PAR measurement from 1 pm until 8 pm on June 28. Average height for Lapriora was 171.20 cm, on average, for all rows. Straight lines in the graph between bulked measurements result from the time units: x-axis is in 100 units, but there are only 60 measurements per hour, taken every minute (e.g. 900-960), then straight from (961-999).

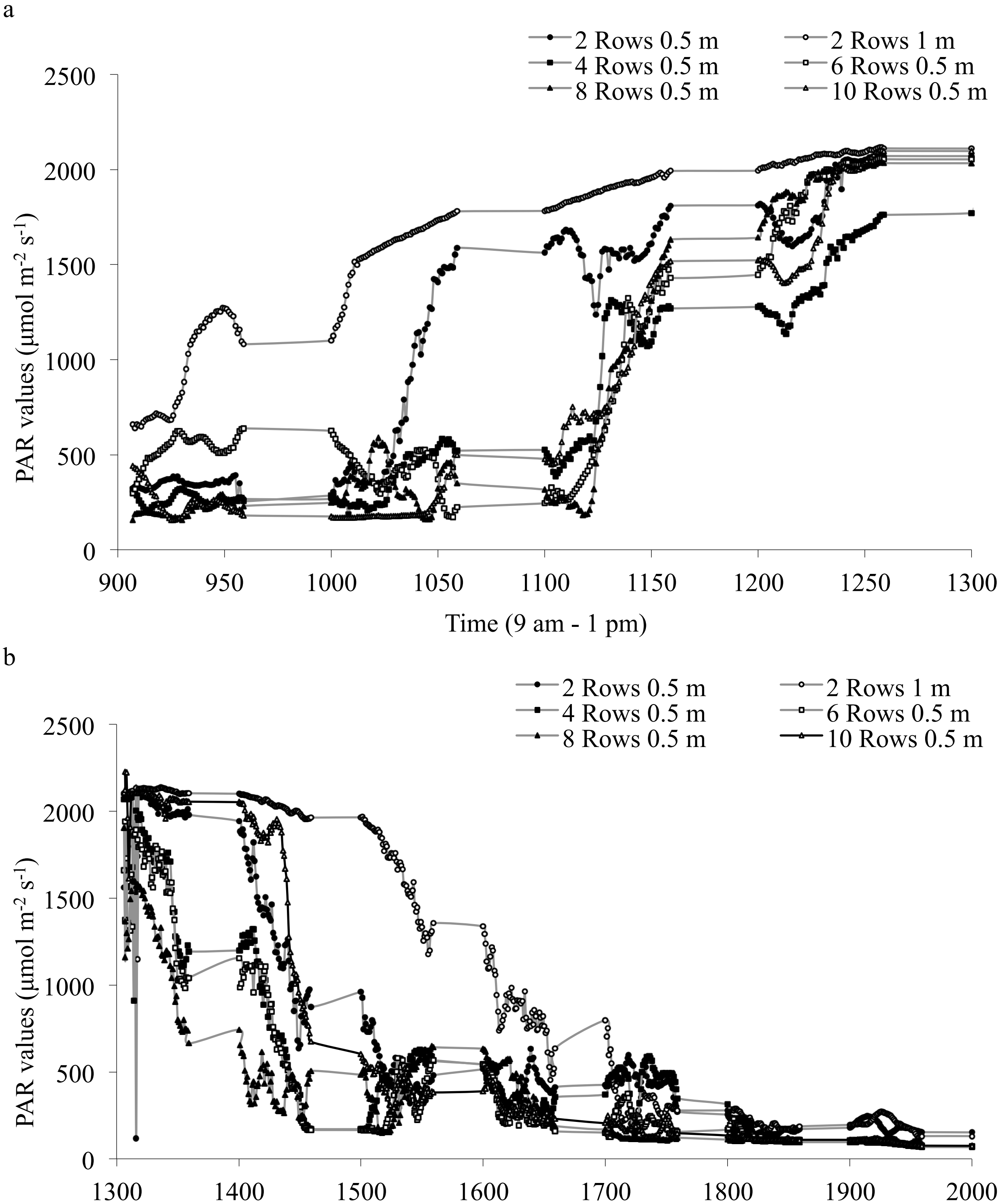


Figure 15. (a) NK-Ravello continuous PAR measurement from 9 am until 1 pm on June 29 [64 days after sowing]. Average height for NK-Ravello was 137.72 cm, on average, for all rows. (b) Amagrano continuous PAR measurement from 1 pm until 8 pm on June 29 [64 days after sowing]. Average height for Amagrano was 187.42 cm, on average, for all rows.

Analysis of yield parameters and row number

The results of the series of two-way ANOVAs run in SPSS, examining the effect that 1) maize cultivar and 2) the border/middle row distinction has on a given dependent variable (maize yield parameter), are included below. There was a statistically significant difference (p=0.022) between plants in border rows and middle rows in terms of the final cobs per plant parameter (border rows had a greater yield), while neither the maize cultivar nor the interaction between cultivar and the border/middle row distinction were significant (figure 16a and table 1). The same two-way ANOVA revealed a similar statistically significant difference between maize plants in the border and middle rows (border rows being greater) in terms of the number of maize cobs per $2m^2$ area of maize plants. The two other terms: 1) cultivar and 2) the interaction of cultivar*border_middle, proved to be non-significant factors in determining the number of maize cobs per $2m^2$ area of maize plants (figure 16b and table 1).

There was a statistically *highly* significant difference between maize cultivars in terms of the weight (in grams) of the total dry matter of cobs per $2m^2$ area for maize (p=0.003). In order from greatest yield to least were Amagrano, Lapriora, and NK-Ravello. The other terms, border_middle, and cultivar*border_middle, did not yield statistically significant results in terms of maize cultivars in terms of the weight (in grams) of the total dry matter of cobs per $2m^2$ area for maize (figure 16c and table 1). In terms of total thousand kernel weight for maize plants, there was a statistically significant difference between maize cultivars (p=0.022). In order from greatest to least thousand kernel weights were Amagrano, NK-Ravello, and Lapriora. The other terms, border_middle and cultivar*border_middle yielded non-statistically significant results (figure 16d and table 1).

For the dependent variable of total kernel number per plant for maize, there was a statistically *highly* significant difference between maize cultivars (p=0.001). In order from greatest final kernel number per plant to least were Amagrano, Lapriora, and NK-Ravello. The other terms (border_middle and cultivar*border_middle) yielded results that were non-significant (figure 16e and table 1). There was a statistically *highly* significant difference between maize cultivars in terms of total dry matter of kernels (in grams) per maize plant at harvest time (p=0.000). In order from greatest yield to least was Amagrano, Lapriora, and NK-Ravello. The analysis also revealed non-statistically significant results for the terms border_middle and cultivar*border_middle in terms of total dry matter of kernels per maize plant (figure 16f and table 1).

There was a statistically *highly* significant difference between maize cultivars in terms of final dry matter of kernels (in grams) per $2m^2$ area for maize plants at harvest. In order of greatest yield to least was Amagrano, Lapriora, and NK-Ravello. The other terms, border_middle and cultivar*border_middle proved to be non-statistically significant (table 1). There was a *highly* significant difference between maize cultivars in terms of total dry matter of kernels (in kg) per 1 ha area of maize plants (p=0.000). In order from greatest yield to least were Amagrano, Lapriora, and NK-Ravello. However, the other factors (border_middle and cultivar*border_middle) yielded non-statistically significant results (table 1). The yield parameters of final dry matter of kernels (grams) per $2m^2$ area and total dry matter of kernels (kg) per 1 ha of maize were included in table 1 for completeness, but they will not be discussed later in the paper, as units in terms of measurements per plant are more generalizable to other agricultural studies.

Table 1. Result of the two-way ANOVAs, which examined the effects that maize cultivar and maize plant location in the plots (border versus middle row) had on yield parameter. Potential interactions between maize cultivar and plant location are also included.

Yield Parameter	**Source**	**Type III SS**	**df**	**MS**	**F**	**p-value**
Cobs per plant	Cultivar	.131	2	.065	3.259	.074
	Border_Middle	.139	1	.139	6.939	.022
	Cultivar*Border_Middle	.016	2	.008	.390	.685
Cobs per 2m^2 area	Cultivar	5.722	2	2.861	.183	.835
	Border_Middle	81.000	1	81.000	5.170	.042
	Cultivar*Border_Middle	19.500	2	9.750	.622	.553
Dry matter cobs (grams) per 2m^2 area	Cultivar	2516159.858	2	1258079.929	9.450	.003
	Border_Middle	438453.658	1	438453.658	3.293	.095
	Cultivar*Border_Middle	33364.817	2	16682.408	.125	.883
Thousand kernel weight (grams)	Cultivar	5064.781	2	2532.391	5.319	.022
	Border_Middle	256.801	1	256.801	.539	.477
	Cultivar*Border_Middle	946.455	2	473.227	.994	.399
Kernel number per plant	Cultivar	61505.735	2	30752.868	12.446	.001
	Border_Middle	10396.181	1	10396.181	4.207	.063
	Cultivar*Border_Middle	731.261	2	365.630	.148	.864
Dry matter kernels (grams)	Cultivar	6916.000	2	3458.000	18.935	.000
	Border_Middle	281.680	1	281.680	1.542	.238
	Cultivar*Border_Middle	457.077	2	228.538	1.251	.321
Dry matter kernels per 2m^2 area	Cultivar	1609297.068	2	804648.534	8.571	.005
	Border_Middle	276018.891	1	276018.891	2.940	.112
	Cultivar*Border_Middle	14127.215	2	7063.608	.075	.928
Dry matter kernels (kg) per hectare	Cultivar	49967335.537	2	24983667.768	18.934	.000
	Border_Middle	2034531.377	1	2034531.377	1.542	.238
	Cultivar*Border_Middle	3301747.312	2	1650873.656	1.251	.321

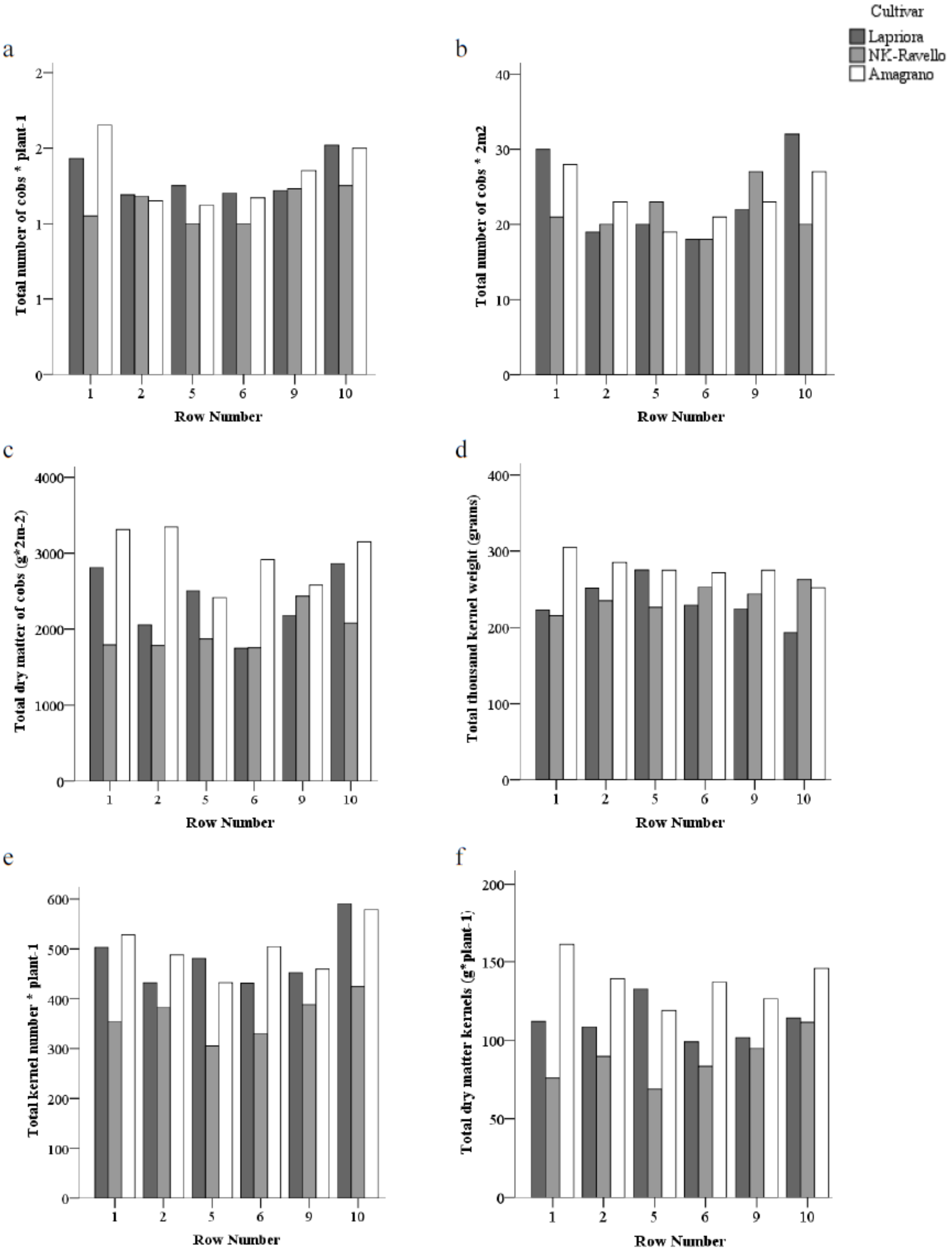


Figure 16. Various maize yield parameters at harvest (October 18 [175 days after sowing]): (a) number of cobs per plant; (b) number of cobs per $2m^2$ area; (c) total dry matter of cobs (grams) per $2m^2$ area; (d) total thousand kernel weight (grams); (e) total kernel number per plant; (f) total dry matter of kernels (grams) per plant.

Tukey's Nonadditivity Test

Table 2. Result of Tukey's Nonadditivity test for various yield parameters in the study. There were two statistically significant results at the α=0.25 level: cobs per plant and cobs per $2m^2$ area. The rest of the yield parameter results were non-significant.

Yield Parameter	Source of Variation	SS	df	MS	F	p-value
Cobs per plant	Between row-cultivar	16.000	2	8.000		
	Within row-cultivar	149.833	5	29.967	2.161	.140
	Nonadditivity	41.363	1	41.363	3.826	.082
	Balance	97.304	9	10.812		
Cobs per $2m^2$ area	Between row-cultivar	.152	2	.076		
	Within row-cultivar	.253	5	.051	3.533	.042
	Nonadditivity	.037	1	.037	3.138	.110
	Balance	.106	9	.012		
Dry matter cobs (grams) per $2m^2$ area	Between row-cultivar	3044224.152	2	1522112.076		
	Within row-cultivar	686012.307	5	137202.461	.992	.469
	Nonadditivity	38004.584	1	38004.584	.254	.626
	Balance	1345422.686	9	149491.410		
Thousand kernel weight (grams)	Between row-cultivar	6908.845	2	3454.423		
	Within row-cultivar	1016.033	5	203.207	.344	.875
	Nonadditivity	85.902	1	85.902	.133	.724
	Balance	5814.986	9	646.110		
Kernel number per plant	Between row-cultivar	64507.399	2	32253.699		
	Within row-cultivar	29753.138	5	5950.628	5.397	.012
	Nonadditivity	711.203	1	711.203	.621	.451
	Balance	10314.879	9	1146.098		
Dry matter kernels (grams)	Between row-cultivar	1921022.286	2	960511.143		
	Within row-cultivar	438121.130	5	87624.226	.895	.520
	Nonadditivity	15728.057	1	15728.057	.147	.710
	Balance	962817.839	9	106979.760		
Dry matter kernels per $2m^2$ area	Between row-cultivar	7679.451	2	3839.725		
	Within row-cultivar	705.304	5	141.061	.634	.679
	Nonadditivity	2.930	1	2.930	.012	.916
	Balance	2221.975	9	246.886		
Dry matter kernels (kg) per hectare	Between row-cultivar	55482569.333	2	27741284.667		
	Within row-cultivar	5096214.618	5	1019242.924	.634	.679
	Nonadditivity	21234.764	1	21234.764	.012	.916
	Balance	16053331.344	9	1783703.483		

Table 3. LAI values for maize plants on July 25, the silking date: BBCH 65 [90 days after sowing].

Row Number	**Lapriora**	**NK-Ravello**	**Amagrano**
4	3067.67	3986.00	4207.67
5	3037.67	3763.67	3846.00
6	3336.33	4234.00	3932.00
7	3128.00	3665.00	3271.67
Average [LA*plant^{-1}]	3142.42	3912.17	3814.33
LAI [cm^2]	26710.54	33253.42	32421.83
LAI [m^2]	2.67	3.33	3.24

Table 3 indicates the calculated LAI for maize plants in different rows at the silking stage (July 25; BBCH 65). Lapriora has the lowest LAI value for the m^2 calculation, followed by Amagrano, and then NK-Ravello (see table 3). From figure 14, we observed that Lapriora transmitted the most radiation in the 2 row systems for all hours measured. We also saw that NK-Ravello had the second-highest PAR transmittance in the 2-row system, and that Amagrano probably had the least PAR transmittance (figure 15). PAR transmittance and LAI are intricately correlated, as a larger leaf area index implies that less radiation would be transmitted to the neighboring crop, as the maize plant is absorbing the incoming solar radiation.

DISCUSSION

Maize Morphology

The finding that Amagrano had the tallest final average plant height, followed by NK-Ravello and Lapriora is consistent with the expected morphologies of these plants: Lapriora had a reduced plant height, NK-Ravello had an increased plant height, and Amagrano had a normal shape (meaning it was expected to have the greatest final height). The finding that average plant height increases with row number is consistent with previous research, which suggests that an increasing plant density for maize plants drives the different plant heights among varying row numbers: higher planting densities have taller final maize plant heights, due to varying intraspecific competition for light resources (Carena and Cross 2003). In our experiment, higher plant density means a larger number of rows per maize strip, or the actual planting density is the same among all strips. Lapriora is a faster-developing cultivar, so it has an increased height earlier in the season (July 5: BBCH 16), which must be considered when thinking about competition for light with a neighboring crop. That is, the cultivar dependent height development depends on the number of growing degree days until a maximum height is reached.

LAI differed greatly between Lapriora and the other maize cultivars (table 3). Lapriora had the lowest LAI values for the m^2 calculation, followed by Amagrano and then NK-Ravello. This is important because, while Amagrano generally had the highest yield in the analyses, it also had the second-highest LAI index, meaning its leaves intercept the most solar radiation compared to the other maize cultivars. That is, while Amagrano maize plants on the border rows generally perform well in this experimental setup, we can infer that a neighboring vegetable crop would have decreased plant growth, due to the intense shading effects of the Amagrano plants with a high LAI index and plant height.

Maize yield and yield components

Overall, there were not equivalent yields among maize cultivars. The statistically significant difference between border and middle rows in terms of the final number of cobs per plant and the final number of cobs per $2m^2$ area suggest that maize plants in the border rows have higher yields than maize plants in the middle rows (table 1). Cobs per $2m^2$ is included in the analyses for completion, although plant number differs between the $2m^2$ samples, and the yield depends largely on the plating density. Cobs per plant is a more generalized unit to compare to other agricultural experiments, so it is the most important yield component in this study. Cobs per plant is highly correlated with PAR around the silking stage (Andrade et al. 2000), so our observed results of Amagrano having the greatest yield with this parameter might not necessarily be associated with its actual physiological advantages. It might be the case that a particularly cloudy or sunny period during maize silking could lead to these results. The kernel set of a second ear is only possible above a certain PAR threshold (e.g. the point when PAR is more than required for the kernel filling of the first cob). More cobs per plant is the principal finding of the yield components across all maize cultivars in this experiment, which is largely determined in the period of maize competitive advantage (Andrade et al. 2000).The remaining six of the maize growth parameters did not exhibit a statistically significant difference between maize plants grown in the border versus the middle rows (table 1).

Lesoing and Francis (1999) found a similar result with a maize/sorghum and soybean strip intercropping setup: the border rows for the maize/sorghum had significant yield increases, but the soybean border-row yields were lower next to all maize and sorghum strips. The maize exhibited increased seed number and seed weight, and the grain sorghum exhibited increased seed number. In each setup, the researchers found that resource competition occurred for maize during the plant reproduction and grain-filling stages. They concluded that strip intercropping had a 4% higher whole-system productivity than the accompanied monocultures, meaning strip intercropping can be equally profitable to monoculture (Lesoing and Francis 1999).

In terms of the differences in final maize plant yield parameters between cultivars, Amagrano is the best performing cultivar. In every two-way ANOVA repetition in which there was a statistically significant difference between cultivars in terms of maize yield, Amagrano had the highest yield (table 1). Highly statistically significant results for the total dry matter of cobs, total kernel number per plant, dry matter kernels per plant (per plant; per $2m^2$ area; per 1 ha) parameters indicate the sharp divisions between cultivars in terms of final maize yield. Further, there was a statistically significant ($p<0.05$) difference between cultivars in terms of thousand kernel weight, with Amagrano yielding the greatest value at harvest (table 1). The second best performing cultivar in terms of final maize plant yield at harvest is Lapriora, with one exception. Lapriora was the second-best cultivar for the total dry matter of cobs, total kernel number per plant, dry matter kernels per plant (per plant; per $2m^2$ area; per 1 ha) parameters, but it was the lowest performing cultivar in terms of thousand kernel weight at harvest (table 1). Increased solar radiation in the border rows of maize might be the primary reason for the additional yield.

While the maize plants would significantly shade a neighboring vegetable crop in an actual intercropping system, this would not necessarily directly decrease the vegetable crop yield. Munz et al. 2011 found that, at harvest, total dry matter of bush bean was increased in row two adjacent to the maize strips, compared to the middle row of the bush bean strips (268). Total dry matter was reduced the most, though, for bush bean in row one adjacent to the maize. Together, these results suggest a positive effect of slight shading on the bush bean growth, to a certain threshold where the reduced solar radiation significantly reduces plant growth (Feike et al. 2010a; Munz et al. 2011, 269). The researchers also found that above a strip width of four maize rows, the total amount of transmitted PAR does not further increase. This finding is consistent with our original hypothesis, although we found that above a strip width of 2 (not 4 rows), there is no additional increase in shading for a vegetable crop. Munz et al. (2011) conclude that using a maize cultivar of reduced plant height and a strip width below six rows of maize optimizes the amount of transmitted radiation to the neighboring bush bean plants; it could improve bush bean plant growth in the first row adjacent to the maize (269).

Although a two-way ANOVA would have been ideal to assess the relative differences between the total yields in different cultivars and within certain rows, I could not perform this analysis due to the nature of my dataset. This is because at least one group in the dataset had fewer than two cases, so there could be no F statistic or p-value in the analysis. The Tukey test for nonaddivity revealed that there were two statistically significant results at the $\alpha=0.25$ level for the dependent variables of cobs per plant and cobs per $2m^2$ area. Again, we are interested in the potential interaction between maize cultivar and row number on a given dependent variable (maize yield parameter). The Tukey test is useful because it addresses this very interaction.

This leads to us rejecting the null hypothesis for two results, but retaining the null hypothesis for the remaining six results. Rejecting the null hypothesis means there is likely an interaction among the variables cultivar, row number, and a dependent variable (cobs per plant or cobs per $2m^2$ area). Retaining the null hypothesis means that there is no interaction among variables in the dataset (Winer 1971, 475). If no interaction effect is found, then all sources of variation other than the main effects are thought to be part of the experimental error (Winer 1971, 394). When an interaction effect is found, it might be considered a measure of nonadditivity of the main effects.

Study limitations

The results of this study are intended to provide data to aid the design of future vegetable strip intercropping studies, and this experimental design has numerous limitations. Again, the fact that we only had one treatment per cultivar means that proper statistical analyses cannot be performed, in the sense that there are no controls or repetitions in the study. Further, we did not take very many solar radiation measurements during the summer next to the maize cultivars. This means it was difficult to correlate plant height and solar radiation regime with a high degree of certainty (although we could use the black box approach to calculate the shadow boundaries for every possible maize plant height). Another limitation was that it was difficult to describe the leaf angle distribution among the maize plants. One of our methods was to use a protractor and record leaf angle distributions for every leaf on selected maize plants, and we tried analysing leaf angles with GIMP2 photo analysis, but there were no significant differences between cultivars. We conclude that leaf angle has a much lower influence on transmitted solar radiation than both plant height and LAI as confirmed by Boote et al. (1994, 1425).

Other limitations relate to the physical development of the maize plants during the growth period. Ihinger Hof received remarkably low rainfall during the critical period of maize development (the bracketing-silking stage), which undoubtedly affected the maize plant growth (61.6 mm precipitation in July). Andrade et al. 2000 noted that the bracketing silking stage in maize plant growth is the most important period when considering plant stresses, with kernel number being an especially crucial yield parameter. An important consideration is that the performance of border plants depends highly on water availability (if nutrients are not limited). That means rainfed systems are only suitable in areas with sufficient rainfall to actually use the increased incoming radiation. That is, this experimental design may not be suitable for all locations, especially those with erratic rainfall. In China, though, the intercropping system works better than in Stuttgart because the farmers irrigate the neighboring vegetable crop; the maize in the border row can readily absorb water to use additional incoming PAR for an increased yield.

Further, the maize kernels in our experiment were not sown with outright precision. A by-product of using a pressurized tractor sowing system was that there was actually more than one plant per space in certain maize rows. This has obvious consequences for intraspecific maize plant competition, so perhaps taking the average of rows five and six would have been desirable than considering each row to be uniform. Another limitation was that any niche differences between intercropped plants that may have existed in a *real* intercrop system would have been minimized in this approach. It is well established that a grass (maize) and legume (bush bean) combination produce better than either in monoculture (Vandermeer 2011). Measuring PAR and LAI were also a challenge, as ideal measurement conditions are when the sky is either completely clear or completely cloudy. Although we did our best to take measurements under homogeneous conditions, heterogeneous conditions tend to lead to non-representative PAR and LAI measurements.

Implications for Chinese food security

Concerned with food security and a growing populace, Chinese agricultural policy has largely focused on improving production and crop yields during the last few decades (China Statistical Yearbook 2008). Although leading to higher agricultural production per land area, these so-called improvements are largely attributed to higher levels of inputs such as synthetic fertilizers, irrigation water, and plant protection (Hebei Statistical Yearbook 2008). Critics warn that these high-intensity cultivation systems have reached their maximum potential in terms of 1) future increases in crop yields with higher input levels and 2) the environment’s capacity to sustain such systems (Feike et al. 2010b).

While breeding better cultivars and developing improved agricultural systems can further increase yields, merely increasing input levels has begun to lose its effectiveness. Some of the most salient consequences of such a system are depleting groundwater tables (Jia et al. 2002), loss of topsoil through erosion (Chen 2007), and accumulating levels of chemical runoff into ground- and surface waters (Li et al. 2009). Further, this high-input, intensive agriculture has led to significant losses of arable land (Dazhong et al. 1992; Brown 1995; Chen 2007), which could greatly impact future generations’ capacity to produce a sufficient quantity of food.

The labor market in China took a dramatic turn in the 1980s with bold market reforms. These reforms accelerated economic growth for the nation, led to improving incomes for families, and re-structured the labor force (Feike et al. 2010b). The latter is directly related to the observation that the farming area under intercropping cultivation has declined in the past two decades. Many workers sought out employment in the industrial and construction sectors, largely abandoning farm work (Hebei Statistical Yearbook 1999-2008).

Researchers have demonstrated that the abundance of small machinery on North China Plain (NCP) farms has *drastically* increased, while that of medium & large machines has steadily increased, suggesting a shrinking agricultural workforce per land area (Hebei Statistical Yearbook 1999-2008; Feike et al. 2010b, 2153). Due to limited off-farm opportunities for income, then, intercropping is most common in remote, rural regions (Feike et al. 2010b). One of the primary obstacles to maintaining intercropping systems in the NCP is in considering the variation between intercropping systems throughout the region. Reforms in the 1980s established the so-called household responsibility system, which divided quality agricultural land equally among households. This split the existing land plots into areas of about 0.07 ha each (Feike et al. 2010b). While this increased biodiversity among plots – as different crops are typically grown in adjacent plots – it required additional labor. But as the agricultural workforce in the NCP continues to erode, land fragmentation is projected to decrease, inviting the possibility for larger-scale machinery (Wan 2001).

Farmer interviews conducted in the North China Plain indicate that motivations for maintaining an intercrop setup are numerous. Among them are that farmers want to optimize their land-use efficiencies, as agricultural production is often a family's single income source, and each family owns less than 0.5 ha, on average (China Statistical Yearbook 2008; Feike et al. 2010b). Farms in an intercrop setup are widely regarded as having fewer pest- and disease issues, meaning farmers can save money through reduced pesticide inputs, thus decreasing environmental degradation. Also, intercropping can yield higher quality products, making it easier for rural farmers to meet export standards (Feike et al. 2010b). Another associated factor – though not widely cited among NCP farmers – is that of reduced crop failure through intercropping. Increased plant diversity means more resilience to external perturbations, whether erratic rainfall or disease outbreaks (Iqdal et al. 2007; Rao and Willey 1980).

These improvements are not without their drawbacks, however. The most important aspect of a traditional intercropping system is that of high labor demand. There are two components to this factor. First, additional labor requirements for these systems are seen through a greater total time spent working in the field. Second, the systems require an increased specialization of labor, as workers must be careful to not damage a second crop when harvesting the first (Feike et al. 2010b).

This study is embedded within the broader aim of evaluating whether or not intercropping of mixed vegetables in the North China Plain has the capacity to be *at least* as productive as highly-intensified, monocrop arrangements into the foreseeable future. Current estimates of intercropping in the NCP for land area under cultivation are five percent, which represents a severe drop since the mid-1990s, when the estimates were around thirty-three percent (Tong 1994; Feike et al. 2010b). That is to say, interest in maintaining traditional intercropping agricultural systems is undoubtedly losing ground, and the pivotal decisions that Chinese policymakers make today could make-or-break the future Chinese food system.

Strip intercropping is a promising candidate, as it 1) maintains the efficiencies & strong yields of intercropping in the border rows and 2) can adapt to the shrinking workforce by allowing for increased mechanization. A reassuring sign that intercropping systems can be maintained is that row intercropping systems are already the most prevalent type in the NCP

(Feike et al. 2010b). The two primary questions become whether farmers should adopt their systems to machines, or whether manufacturers should adopt agricultural machinery to the systems. Given the tremendous variability in NCP intercropping systems, it seems unlikely that the latter would be the case. Mass-production of machinery is the most economical for agricultural companies, and critics warn that the only systems that can substantially benefit the environment are those that are widely adapted (Feike et al. 2010b).

CONCLUSION

Recent research in China has focused primarily on agronomic advantages of intercropping, neglecting the connections between the socio-economic developments and farmers' decisions in the fields. While improvements in pure agronomic output are an important component of a nation's food policy program, they are certainly *not* a panacea. Planners should recognize that there are a myriad of other, perhaps equally important, components to a resilient food system, such as social cohesion, environmental sustainability, and cultural survival (Perfecto et al. 2009). Intercropping has the potential to compensate for the observed environmental degradation in the region, as well as the socio-economic shift towards urban areas from the NCP, but intercropping systems must be designed well, incorporating local demand for certain crops as well as climatic conditions in the region.

The results of this experiment indicated that the larger number of cobs per plant is consistent across maize cultivars, suggesting the benefits of using hybrid varieties with strong prolificacy, especially in high solar radiation conditions, like the NCP, to increase the crop yield in the border rows. The highest yielding maize cultivar, Amagrano, also had the highest plant height during the growing season, as well as the second-highest LAI index, which complicates the task of choosing an appropriate cultivar for the strip intercropping of maize with a shorter vegetable. While high yield is the primary concern in the systems, the strong maize shading characteristics would counteract the productivity of the neighboring crop. For future intercropping studies, improvement of plant growth modeling is essential to gain a deeper insight into temporal and spatial plant competition, thereby optimizing the systems. It is important to account for the interactions between the crops to optimize the overall system productivity. Our R code could be improved to include maize plant height in relation to growing degree days by linking the two codes, in order to use temperature data for other years and locations. Regionalizing the suitability of strip intercropping for China, Germany and possible other regions with varied weather, soil, and especially irrigation conditions is also essential for future agricultural planning.

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REFERENCES

Alene, A.D. and R.M. Hassan. 2003. Total factor productivity and resource use efficiency of alternative cropping systems in two agro-climatic zones in eastern Ethiopia. *Agricultural Economics Review*, no. 4: 32-47.

Andrade, Fernando H., Otegui, Maria E., and Vega, Claudia. 2000. Intercepted Radiation at Flowering and Kernel Number in Maize. *Agron. J.*, no. 92:92-97.

Boehmel, Constanze, Iris Lewandowski, and Wilhelm Claupein. 2008. Comparing annual and perennial energy cropping systems with different management intensities. *Agricultural Systems* 96, no. 1: 224.

BOOTE, KJ and NB PICKERING. 1994. MODELING PHOTOSYNTHESIS OF ROW CROP CANOPIES. *HortScience* 29, no. 12: 1423.

BROWN, GP. 1995. ARABLE LAND LOSS IN RURAL CHINA - POLICY AND IMPLEMENTATION IN JIANGSU PROVINCE. *ASIAN SURVEY* 35, no. 10: 922.

Carena, M.J. and H.Z. Cross. 2003. Plant Density and Maize Germplasm Improvement in the Northern Corn Belt. *Maydica* 48: 105-111.

Carrubbaa, A., R. la Torre, F. Saiano, and P. Aiello. 2008. Sustainable production of fennel and dill by intercropping. *AGRONOMY FOR SUSTAINABLE DEVELOPMENT* 28, no. 2: 247.

CHANDLER, P. 1994. ADAPTIVE ECOLOGY OF TRADITIONALLY DERIVED AGROFORESTRY IN CHINA. *Human Ecology* 22, no. 4: 415.

Chen, J. 2007. Rapid urbanization in china: A real challenge to soil protection and food security. *Catena* 69, no. 1: 1.

China Statistical Yearbook. China Statistical Press, Beijing, China, 2008.

Cruse, Richard M. 2008. Strip Intercropping: A CRP Conversion Option | Conservation Reserve Program: Issues and Options. Iowa State University Extension and Outreach. https://store.extension.iastate.edu/ItemDetail.aspx?ProductID=1103 (Accessed April 12, 2012).

Dazhong, W., Yingxin, T., Xunhua, Z., and Yungzhen, H. 1992. Sustainable and productive agricultural development in China. *Agriculture, Ecosystems, and Environment* 39: 55-70.

Feike, Til, Munz, Sebastian, Graeff-Hönninger, Simone, Chen, Qing, Pfenning, Judit, Zühlke, Gudrun, and Claupein, Wilhelm. 2010a. Light competition in Chinese cabbage/maize strip intercropping systems. Paper presented at Precision Agriculture Reloaded – Informationsgestützte Landwirtschaft Referate der 30. GIL Jahrestagung [Informationbased agriculture: Sections of the 30th GIL Annual Conference]. Stuttgart, Germany. February 24-25.

Feike, Til, Chen, Qing, Pfenning, Judit, Graeff-Hönninger, Simone, Zühlke, Gudrun, and Claupein, Wilhelm. 2010b. How to overcome the slow death of intercropping in China. Paper presented at the 9th European International Farming Systems Association Symposium, Vienna, Austria. July 4-7.

Feike, Til, Qing Chen, Simone Graeff-Hönninger, Judit Pfenning, and Wilhelm Claupein. 2010c. Farmer-developed vegetable intercropping systems in southern Hebei, China. *Renewable Agriculture and Food Systems* 25, no. 4: 272.

Ghaffarzadeh, M., F. G. Prechac, and R. M. Cruse. 1994. Grain yield response of corn, soybean, and oat grown in a strip intercropping system. *American Journal of Alternative Agriculture* 9, no. 4: 171-177.

Ghaffarzadeh, M., FG Prechac, and RM Cruse. 1997. Tillage effect on soil water content and corn yield in a strip intercropping system. *Agronomy Journal* 89, no. 6: 893.

Goudriann, J. 1977. Crop Micrometeorology: a Simulation Study. *Simulation Monographs*, Pudoc, Wageningen, 249 pp.

Goudriann, J. 1988. The bare bones of leaf-angle distribution in radiation models for canopy photosynthesis and energy exchange. *Agricultural and Forest Meteorology* 43: 155-169.

Hebei Statistical Yearbook. China Statistical Press, Beijing, China, 1999-2008.

Innis, D.Q. 1997. Intercropping and the Scientific Basis of Traditional Agriculture, Intermediate Technology Publications, Ltd., London.

Iqbal, J., Z. A. Cheema, and M. An. 2007. Intercropping of field crops in cotton for the management of Purple Nutsedge (*Cyperus rotundus* L.). *Plant and Soil* 300, no. 1: 163.

Jia, J., Yu, J. and C. Liu. 2002. Groundwater regime and calculation of yield response in North China Plain: a case study of Luancheng County in Hebei Province. *J. of Geographical Sciences* 12, no. 2 : 217-225.

Jin-sheng, Jia, Yu Jing-jie, and Liu Chang-ming. 2002. Groundwater regime and calculation of yield response in North China Plain: A case study of Luancheng County in Hebei Province. *Journal of Geographical Sciences* 12, no. 2: 217.

Jolliffe, P.A. 1997. Are mixed populations of plant species more productive than pure stands? *Acta Oecologica Scandinavica* (OIKOS) 80:3, issued by the Nordic Society, 595-602.

Keating, B. A. and P. S. Carberry. 1993. Resource capture and use in intercropping: Solar radiation. *Field Crops Research* 34, no. 3: 273.

Knörzer, Heike, Graeff-Hönninger, Simone, Guo, Buqing, Wang, Pu, and Claupein, Wilhelm. 2009. The Rediscovery of Intercropping in China: A Traditional Cropping System for Future Chinese Agriculture – A Review. *Climate Change, Intercropping, Pest Control and Beneficial Microorganisms, Sustainable Agriculture Reviews* 2: 13-44.

Lancashire, P.D., Bleiholder, H., Van den Boom, T., Langelüddecke P., Stauss, R., Weber, E., and Witzenberger, A. 1991. A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology*, 119, no. 3: 561-601.

Lesoing, Gary W. and Charles A. Francis. 1999. Strip intercropping effects on yield and yield components of corn, grain sorghum, and soybean. *Agronomy Journal* 91, no. 5: 807.

Li, Long, Xiaolin Li, Jianhao Sun, Fusuo Zhang, Zdenko Rengel, and Sicun Yang. 2001. Wheat/maize or wheat/soybean strip intercropping. *Field Crops Research* 71, no. 3: 173.

Li, Yunfeng, Weifeng Wan, Jin Song, Yaoguo Wu, Yanjuan Xu, and Maosheng Zhang. 2009. Classification of groundwater contamination in Yuxi River Valley, Shaanxi Province, China. *Bulletin of Environmental Contamination and Toxicology* 82, no. 2: 234.

Michalsky, Joseph J. 1988. The astronomical almanac's algorithm for approximate solar position (1950–2050). *Solar Energy* 40, no. 3: 227.

Michalsky, J.J. Errata. 1989. *Solar Energy* 43, no. 5: 323.

Müller, Anke, Til Feike, Qing Chen, Simone Gräff-Hönninger, Judith Pfenning, Wilhelm Claupein. 2009. Developing an Improved Strip-intercropping System for Maize and Chinese Cabbage in the North China Plain. Paper presented at the Conference on International Research on Food Security, Natural Resource Management and Rural Development, University of Hamburg, Germany. October 6-8.

Munz, Sebastian, Graeff-Hönninger, S., and Claupein, W. 2011. How to manage above-ground competition in bush bean/spring maize strip-intercropping? Abstract. Paper presented at the Gemeinsame Tagung Deutsche Gesellschaft für Pflanzenzernährung e. V. Gesellschaft für Pflanzenbauwissenschaften e. V. sowie 54. Jahrestagung der GPW Kiel Stickstoff in Pflanze, Boden und Umwelt Kurzfassungen der Vorträge und Poster [Joint Meeting of the German Society for Plant Nutrition V. Society of Agronomy V. as well as the 54th Annual Meeting of the GPW: Nitrogen in plants, soil, and the environment. Abstracts of papers and posters]. (September 27-29): 268-269.

Perfecto, Ivette, Vandermeer, John, and Wright, Angus. 2009. *Nature's Matrix: Linking Agriculture, Conservation and Food Sovereignty*. London: Earthscan.

Pronk, A. A., J. Goudriaan, E. Stilma, and H. Challa. 2003. A simple method to estimate radiation interception by nursery stock conifers: A case study of eastern white cedar. *NJAS - Wageningen Journal of Life Sciences* 51, no. 3: 279.

Rao, M.R. and R.W. Willey. 1980. Evaluation of Yield Stability in Intercropping: Studies on Sorghum/Pigeonpea. *Experimental Agriculture*, no. 16 : 105-116.

Spencer, J. W. 1989. Comments on the astronomical almanac's algorithm for approximate solar position (1950–2050). *Solar Energy* 42, no. 4: 353.

Stack Overflow. http://stackoverflow.com/questions/8708048/position-of-the-sun-given-time-of-day-latitude-and-longitude/ (accessed March 22, 2012).

Tong, P.Y. 1994. Achievements and perspectives of tillage and cropping systems in China. *Cropping System and Cultivation Technology* (Genzuo Yu Zaipei) 77: 1-5.

Tsubo, M., Walker, S., and Mukhala, E. 2001. Comparisons of radiation use efficiency of mono-/inter-cropping systems with different row orientations. *Field Crops Research* 71 (February): 17-29.

U.S. Central Intelligence Agency. 2011. The World Factbook. East & Southeast Asia: China. *People and Society*. Washington, D.C.

Vandermeer, John H. 2011. *The Ecology of Agroecosystems*. Sudbury, Mass.: Jones and Bartlett Publishers.

Vandermeer, John H. 1989. *The Ecology of Intercropping*. Cambridge [England]; New York: Cambridge University Press.

Wahua, T.A.T. 1985. Effects of Melon (*Colocynthis vulgaris*) Population Density on Intercropped Maize (*Zea mays*) and Melon. *Experimental Agriculture* 21: 281-289.

Walker, S. and H. O. Ogindo. 2003. The water budget of rainfed maize and bean intercrop. *Physics and Chemistry of the Earth* 28, no. 20: 919.

Walraven, Robert. 1978. Calculating the position of the sun. *Solar Energy* 20, no. 5: 393.

Wan, Guang H. and Enjiang Cheng. 2001. Effects of land fragmentation and returns to scale in the chinese farming sector. *Applied Economics* 33, no. 2: 183.

WEST, TD and DR GRIFFITH. 1992. EFFECT OF STRIP-INTERCROPPING CORN AND SOYBEAN ON YIELD AND PROFIT. *Journal of Production Agriculture* 5, no. 1: 107.

Whitmore, A. P. and J. J. Schröder. 2007. Intercropping reduces nitrate leaching from under field crops without loss of yield: A modelling study. *European Journal of Agronomy* 27, no. 1: 81.

Winer, B.J. 1971. *Statistical Principles in Experimental Design.* McGraw-Hill Book Company.

Zhang, F. and Li, L. 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil* 248: 305-312.

Appendix A. R code and graphical output

```
ShadowLength <- function(year, month, day, hour, min,
                         pH, lat=48.46, long=8.56, raz=0) {

   twopi <- 2 * pi
   deg2rad <- pi / 180
   sec <- 0

   # Get day of the year, e.g. Feb 1 = 32, Mar 1 = 61 on leap years
   month.days <- c(0,31,28,31,30,31,30,31,31,30,31,30)
   day <- day + cumsum(month.days)[month]
   leapdays <- year %% 4 == 0 & (year %% 400 == 0 | year %% 100 != 0) & day >=   60
   day[leapdays] <- day[leapdays] + 1

   # Get Julian date - 2400000
   hour <- hour + min / 60 + sec / 3600 # hour plus fraction
   delta <- year - 1949
   leap <- trunc(delta / 4) # former leapyears
   jd <- 32916.5 + delta * 365 + leap + day + hour / 24

   # The input to the Astronomer's almanac is the difference between
   # the Julian date and JD 2451545.0 (noon, 1 January 2000)
   time <- jd - 51545

   # Ecliptic coordinates

   # Mean longitude
   mnlong <- 280.460 + 0.9856474 * time
   mnlong <- mnlong %% 360
   mnlong[mnlong < 0] <- mnlong[mnlong < 0] + 360

   # Mean anomaly
   mnanom <- 357.528 + 0.9856003 * time
   mnanom <- mnanom %% 360
   mnanom[mnanom < 0] <- mnanom[mnanom < 0] + 360
   mnanom <- mnanom * deg2rad

   # Ecliptic longitude and obliquity of ecliptic
   eclong <- mnlong + 1.915 * sin(mnanom) + 0.020 * sin(2 * mnanom)
   eclong <- eclong %% 360
   eclong[eclong < 0] <- eclong[eclong < 0] + 360
   oblqec <- 23.429 - 0.0000004 * time
   eclong <- eclong * deg2rad
   oblqec <- oblqec * deg2rad

   # Celestial coordinates
   # Right ascension and declination
   num <- cos(oblqec) * sin(eclong)
   den <- cos(eclong)
   ra <- atan(num / den)
   ra[den < 0] <- ra[den < 0] + pi
   ra[den >= 0 & num < 0] <- ra[den >= 0 & num < 0] + twopi
   dec <- asin(sin(oblqec) * sin(eclong))
```

```
   # Local coordinates
   # Greenwich mean sidereal time
   gmst <- 6.697375 + .0657098242 * time + hour
   gmst <- gmst %% 24
   gmst[gmst < 0] <- gmst[gmst < 0] + 24.

   # Local mean sidereal time
   lmst <- gmst + long / 15.
   lmst <- lmst %% 24.
   lmst[lmst < 0] <- lmst[lmst < 0] + 24.
   lmst <- lmst * 15. * deg2rad

   # Hour angle
   ha <- lmst - ra
   ha[ha < -pi] <- ha[ha < -pi] + twopi
   ha[ha > pi] <- ha[ha > pi] - twopi

   # Latitude to radians
   lat <- lat * deg2rad

   # Azimuth and elevation
   el <- asin(sin(dec) * sin(lat) + cos(dec) * cos(lat) * cos(ha))
   az <- asin(-cos(dec) * sin(ha) / cos(el))
   cosAzPos <- (0 <= sin(dec) - sin(el) * sin(lat))
   sinAzNeg <- (sin(az) < 0)
   az[cosAzPos & sinAzNeg] <- az[cosAzPos & sinAzNeg] + twopi
   az[!cosAzPos] <- pi - az[!cosAzPos]


   #--------Begin adapted code------------
   # shadow length
   tanel <- (1/tan(el))
   SL <- pH * tanel
   ALP <- az - raz

   #ShadowLength perpendicular to the row (SLPe)
   tanelsin <- ((1/tan(el)) * sin(ALP))
   SLPe <- pH * tanelsin

   #----------End adapted code-------------


   # here: backtransformation to degrees:
   el <- el / deg2rad
   az <- az / deg2rad
   lat <- lat / deg2rad

   return(SLPe)
 }


# test
result <- ShadowLength(year=2010, month=5, day=1, hour=1, min=1,
```

```
                       pH=200, lat=46.5, long=6.5, raz=0)

result

#loop over one day
result <- c()
for(h in 5:16){
  for(m in 1:60){
    result <- append(result,
                     ShadowLength(year=2009, month=7, day=21, hour=h, min=m,
                                pH=100, lat=46.5, long=6.5, raz=0) )
  }
}

# plot results of one day
plot(result, type="l",
     ylab="Shadow length",
     xlab="Minute",
     lwd=2, col="darkblue")

abline(v=60, col="red", lwd=2)
abline(h=0, col="red", lwd=2)
#-----------------------------------------------------
# loop for determining break point (shadow < 60)

# 1. set variables

# 2. run loop
hresult <- c()
mresult <- c()
sresult <- c()

for(h in 5:18){ # loop over hours
  for(m in 1:60){ # loop over minutes

    # intermediate result:
    s <- ShadowLength(year=2011,month=7,day=16,h,m,
                      pH=230,lat=48.46,long=8.56, raz=0)

    hresult <- append(hresult, h)
    mresult <- append(mresult, m)
    sresult <- append(sresult, s)

  } # close loop over minutes
} # close loop over hours

result <- cbind(hour=hresult, minute=mresult, shadow=sresult)
result

# plot certain hour
plot(result[hresult == 5:16,'shadow'],
     type="l", lwd=2, col="gray", xlab="Time (minutes)")
points(result[hresult == 5:16,'shadow'],
     pch=19, col="black")
```

```
# reduce whole dataset to shadow < 0
Zen <- result[which(sresult < 0), ]
# take the highest one of reduced set
Zen[which( Zen[,3] == max(Zen[,3])), ]

# reduce whole dataset to shadow < 437
MORow1 <- result[which(sresult < 437), ]
# take the highest one of reduced set
MORow1[which( MORow1[,3] == max(MORow1[,3])), ]

# reduce whole dataset to shadow < 387
MORow2 <- result[which(sresult < 387), ]
# take the highest one of reduced set
MORow2[which( MORow2[,3] == max(MORow2[,3])), ]

# reduce whole dataset to shadow < 237
MORow5 <- result[which(sresult < 237), ]
# take the highest one of reduced set
MORow5[which( MORow5[,3] == max(MORow5[,3])), ]

# reduce whole dataset to shadow < -87.5
AFRow1 <- result[which(sresult < -87.5), ]
# take the highest one of reduced set
AFRow1[which( AFRow1[,3] == max(AFRow1[,3])), ]

# reduce whole dataset to shadow < -137.5
AFRow2 <- result[which(sresult < -137.5), ]
# take the highest one of reduced set
AFRow2[which( AFRow2[,3] == max(AFRow2[,3])), ]

# reduce whole dataset to shadow < -287.5
AFRow5 <- result[which(sresult < -287.5), ]
# take the highest one of reduced set
AFRow5[which( AFRow5[,3] == max(AFRow5[,3])), ]
```

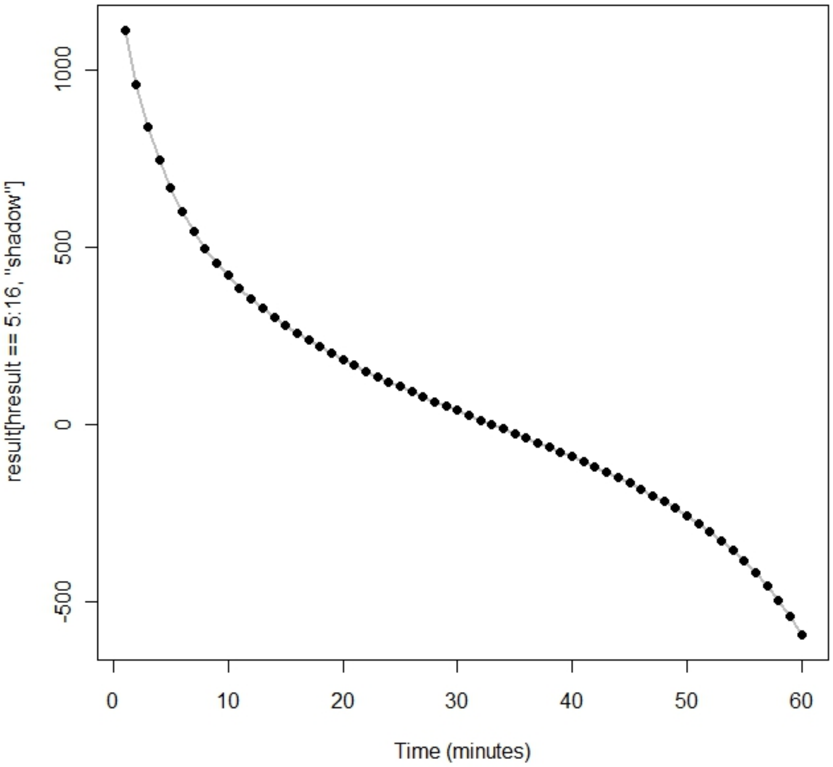

Figure 17. R graphical output for casted shadow length perpendicular to maize rows. Parameters are set to the coordinates of Ihinger Hof station in Germany, for July 16, 2011. This could be adapted to fit the needs of farmers in other locations, as well as for different times of the year, varying maize plant heights, distance to the neighboring crop. The height of the neighboring crop could be included in the code, in order to determine the time at which the crop would receive full sun (taller plants would receive full sun earlier).