Dissecting maize matter production variability using a structural model – An original approach to drive maize breeding for cold tolerance

G. LOUARN[1], K. CHENU[1], C. FOURNIER[2], B. ANDRIEU[2] and C. GIAUFFRET[1]

[1]UMR 1281 SADV, INRA-USTL, Estrées-Mons, BP 136, F80203 Péronne, France
[2]UMR1091 Environnement et Grandes Cultures, INRA, AgroParisTech, F78850 Thiverval – Grignon

Backgrounds and Aims –

Plant response to temperature is one of the most important factors governing the yield of crops. Many crops are however cultivated well outside their original zones of natural selection, and hence are bound to experience temperatures out of their optimal range, with potentially detrimental effects on matter production and yield elaboration. In maize, a cold sensitive species of subtropical origin, breeders have so far extended cultivation areas by using predominantly shunting strategies (selection of early-maturing photoperiod-insensitive hybrids). In northern Europe, this leads to growing cycles taking place during a climatic window reasonably favourable in terms of temperatures but presenting frequent water shortage from the critical flowering stage on, and decreasing light availability during grain filling. Because earlier sowing would allow a better fit between crop cycle and overall resource availability, breeders are now seeking for original adaptation strategies enabling plants to grow more efficiently under cool temperature conditions (Greaves, 1996).

Suboptimal temperatures have a major impact on radiation interception through modification of foliage development (Chenu *et al*., 2007) and on radiation use efficiency (RUE) through the reduction of leaf photosynthetic activity (Dolstra *et al*., 1994). However, our limited understanding of how these processes interact in the course of canopy development and our knowledge of their genetic variability still hamper our ability to define relevant selection criteria to improve productivity in a realistic range of climatic scenarios. A modelling approach able to sort out the processes involved in different climatic scenarios would help making sensible decisions according to breeders' objectives. Such a tool has to rely on an organ scale description of plant structure in order to deal with the heterogeneous canopy structure when cold stresses usually occurs (early growth stages).

This study quantifies, for four contrasted inbred lines grown in climatic sequences including periods of suboptimal temperatures, the impact of architectural traits involved in light interception and of RUE on biomass production. It implied the calibration and assessment of the 3D model, ADEL-maize (Fournier and Andrieu, 1998) for each of the studied genotypes and its use, together with a radiosity model (Chelle and Andrieu, 1998), to calculate light absorption by plants.

Materials and Methods –

Field experiments were carried out at Estrées-Mons (49°N, 3°E, 85m), France, in 2005 and 2006 with four cold-tolerant inbred lines (F2 and F286 from temperate origin; F331 and F334 from tropical-highland origin). In both experiments, two sowing dates (early: first week of April; normal: first week of May) were used to generate contrasted temperature regimes during seedling establishment. In addition, the two years differed in the temperature conditions during this period (Fig. 1): in 2005 cold stress occurred only for the early sown plants before the stage "emergence of the 3rd leaf", while in 2006 it affected early sown plants during short periods at the stage "emergence of the 2nd leaf" and at the beginning of their autotrophic phase (6 unfolded leaves), and normally sown seedlings in their very first stage of development.

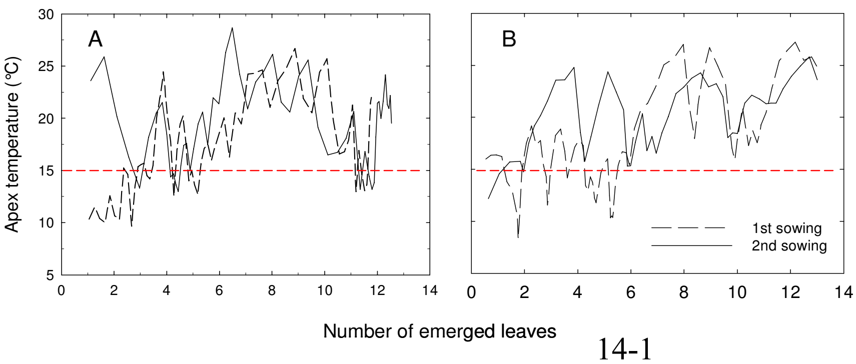


Figure 1: Apex temperatures over plant development expressed in number of emerged leaves for the inbred line F2, in the 2005 (A) and 2006 (B) experiments. Red dashes represent the temperature below which cold stress occurs in maize.

For each situation, plant phenology, leaf senescence and plant architecture were characterised over time. These records enabled the analysis of the plant architecture modifications in response to low temperatures and to parameterise the 3D model (i.e. define plant phyllochrone, organ dimensions and leaf shapes in each situation). Measurements of ground cover were performed to assess the quality of the generated virtual plants (comparison of real and computer-generated pictures). Destructive biomass measurements were made to determined RUE (ratio between above ground biomass and cumulated intercepted PAR) from simulation of radiative transfer within the virtual stands. Finally, we carried out a sensitivity analysis to evaluate the relative importance of architectural traits (leaf length, leaf width, shape of the vertical profile of leaf area, leaf angles, internode length) and of the photosynthetic activity with respects to dry matter production and available genotypic variability.

Main results –

Low temperatures modified plant development during and after the cold period. Inbred lines exhibited a range of phyllochron sensitivity (F334 systematically increased its phyllochron for early sowing while F286 remained unaffected; F2 and F331 were affected in 2005 but unaffected in 2006). Leaf lifespan also showed a strong response to cold stress, senescence being hastened for early sowings (Fig. 2). Interestingly, this response was more pronounced in 2006, when the cold period extended in June concomitantly with high incoming PAR radiation. It suggests possible interactions between plant functioning (i.e. photoinhibition induced by the imbalance between intercepted energy and the reduction capacity of leaves at low temperature, Fig. 3) and the dynamic evolution of its structure that are potentially important during seedling establishment.

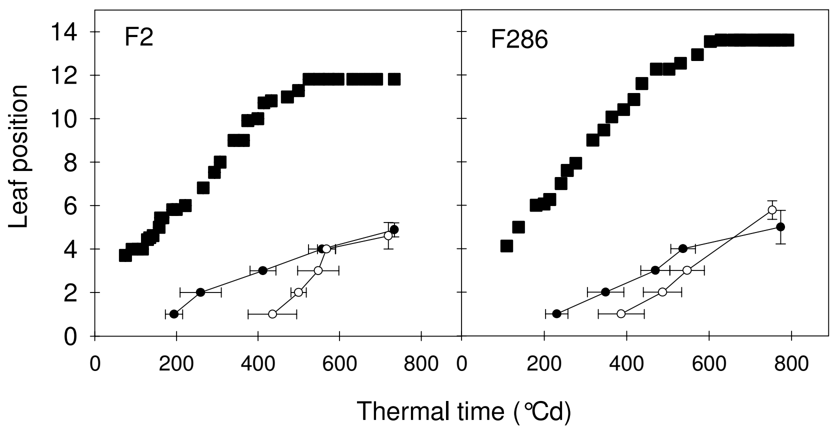
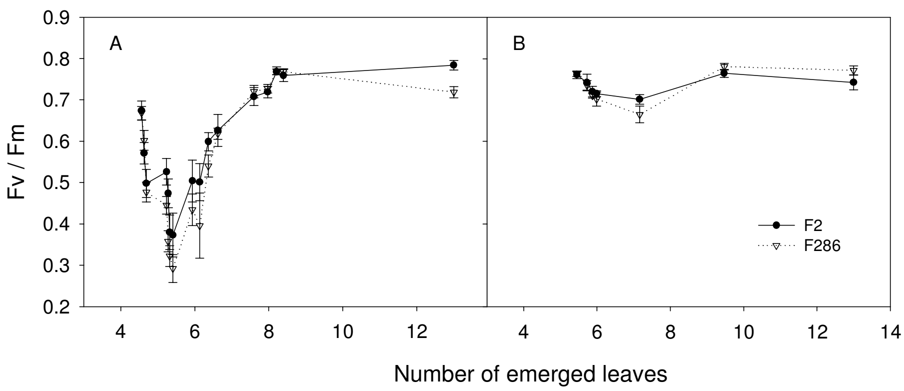


Figure 2: Thermal time of leaf emergence (squares) and of leaf senescence (circles) for early (plain symbols) and normal (open symbols) sowings in the 2006 experiment (F2 and F286 inbred lines).

.

Figure 3: Efficiency of the photosystem II (Fv/Fm) as a function of plant development for early (A) and normal (B) sowings in the 2006 experiment (F2 and F286 inbred lines).



Whatever the genotype considered, length and width of mature leaves were severely reduced for early sowings (Fig. 4), some inbred lines being more prone to this effect of suboptimal temperatures on leaf expansion (F2 being the most and F331 the less sensitive lines). Modification of the leaf area profiles seemed to initiate only after the first occurrence of a significant thermal stress (later in 2006 than in 2005), then propagating until the topmost leaves for all lines but F331 (delayed tassel initiation in this genotype resulting in a significant increase of the final number of leaves).

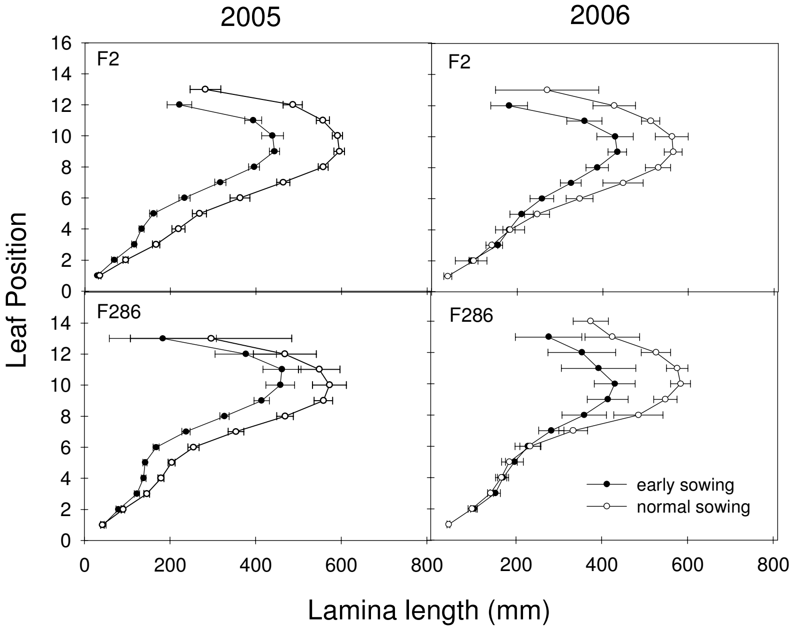


Figure 4: Final lamina length of successive leaves along the shoot for early and normal sowings in the 2006 experiment (F2 and F286 inbred lines).

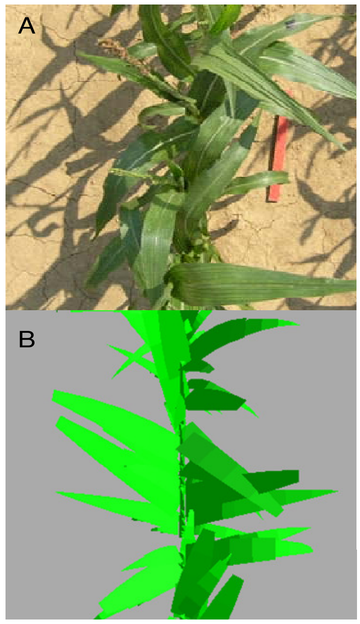


Figure 5: Examples of real (A) and generated (B) images used for virtual plants assessment (F2 inbred line at flowering)

Biomass production was also reduced for early sowing in both years. Relative reduction was lower in 2006 and ranking of inbred lines also changed (F2 exhibited the strongest response in 2005 but the slightest in 2006).

Collected developmental and architectural data were used to fit the simulation model ADEL-maize. Generated 3D virtual stands were successfully assessed against ground cover measurements at various developmental stages (Fig. 5). Special attention was paid to the period of seedling establishment as it corresponds to the period during which cold stress and photoinhibition most likely occur (and thus to the most relevant period to identify potential reductions of RUE). Computation of light interception on these validated mock-ups revealed that the contribution of RUE to the reduction of biomass accumulated at flowering was marginal as compared to the impact of cumulative radiation captured in 2005. It also highlighted potentially important transient effects of RUE during early stages for climatic scenarios leading to photoinhibition.

The sensitivity analysis allowed us to identify that stability of final leaf number, final leaf area and RUE are the traits affecting most directly the stability of matter production under cold conditions. Among them, organ size-related traits displayed the most interesting genotypic variability.

Conclusion –

In this study virtual plants coupled with a biophysical model of radiative transfer helped to better characterise plant response to contrasted cold stresses through accurate quantification of light interception. These results constitute a first step toward a tool for phenotyping plant response to low temperature, considering both plant structure and functioning.

Key Words: maize, low temperature, light interception, RUE, genetic variability, virtual plants

References –

Chelle C., Andrieu B. 1998. The nested radiosity model for the distribution of light within plant canopies. *Ecological Modelling* **111**: 75-91.

Chenu K., Fournier C., Andrieu B., Giauffret C., 2007. An architectural approach to investigate maize response to low temperature. *Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations. J.H.J. Spiertz, P.C. Struick and H.H. van Laar (eds.), 2007 Springer, The Netherlands*, pp 201-210.

Dolstra O., Haalstra S.R., Van der Putten P.E.L., Schapendonk AHCM., 1994. Genetic variation for resistance to low temperature photoinhibition of photosynthesis in maize. *Euphytica*, 80: 85-93.

Fournier C, Andrieu B. 1998. A 3D architectural and process-based model of maize development. *Annals of Botany* **81**: 233-250.

Greaves J.A., 1996. Improving suboptimal temperature tolerance in maize – the search for variation. *J. Exp. Bot*., 47:307-323.