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Transplant in Sweet Maize: A Tool for Improving Productivity

Adalberto Di Benedetto[1,2*] **• Jorge Rattin**[2]

[1] Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453 (C1417DSE), Buenos Aires, Argentina
[2] Facultad de Ciencias Agrarias, Universidad de Mar del Plata, Ruta 226 Km. 73,5 Balcarce, Provincia de Buenos Aires, Argentina
Corresponding author: * **dibenede@agro.uba.ar**

ABSTRACT

An understanding of the response of sweet maize to particular short- and long-term stresses is limited even further by interactions with other stresses in the crop such as the root restriction imposed by small plug cell trays when a transplant routine is used. It is possible to obtain higher yield from sweet maize plants using a transplant method rather than direct seeding under optimal environments. Decreased shoot growth observed in transplanted maize seedlings is related to root restriction caused by the size of the previous container but does not affect mechanical impedance to any extreme level. Inadequate temperature, which is common following seeding in short-season areas, and which reduces both seedling emergence and leaf appearance rates and makes seeds and seedlings susceptible to disease organisms, leads to reduction in seedling vigor. According to the our experiments conducted in a marginal maize production area, transplanting sown sweet maize hybrids showed changes in dry weight accumulation, increased light interception, harvest index, radiation use efficiency and yield. We have been able to optimize plant density to almost 12 plants m^{-2} although daily maximum and minimum temperatures during the first stages of vegetative growth must be controlled. The economic feasibility for Argentina of transplant when such high density was used showed that the added cost of transplant is often possible.

Keywords: harvest index, leaf development, plant density, radiation use efficiency, sowing routine, yield

CONTENTS

INTRODUCTION

Agricultural management practices and hybrids have markedly changed over the last three decades, with decreased tillage, increased residue inputs, and increased crop yields (Suyker *et al*. 2004).

Corn production has been extended into short-season areas during the course of the last century. Selection for better-adapted hybrids with high yield potentials has altered morphological traits (e.g. plant height, leaf number and size) that are important components of canopy architecture. Canopy architecture influences many canopy processes including interactions between the crop and specific aspects of its environment. Canopy architecture is a function of leaf number, shape, distribution, orientation, and plant size, which collectively determine the vertical distribution of light within the corn canopy (Begna *et al*. 2001a).

Agricultural Experiment Stations throughout the North Central States (US) have generally reported yield advantages from planting corn early (late April or early May) (Pendleton and Egli 1969). By the other hand, numerous studies on maize physiology and agronomy suggest that agro-climatic conditions in northern Europe are not ideally suited to maize as a grain crop, which needs to be sown late in order to avoid spring frost during germination and early seedling growth, and at the end of the growing season grain-filling often coincides with autumn frosts and adverse soil conditions, which can impede harvest procedures (Dale and Drennan 1997a). Such studies arouse interest in what the yield potential might be if corn were to be planted even earlier.

Marketability of hybrid sweet corn is, in part, dependent on sugar content in kernels (Lertrat and Pulam 2007). Sugars are produced in leaves, pass through the vascular system to support physiological processes, and are deposited in kernels. Sugar transport may be interrupted and sugar deposition in kernels affected if plant development is compromised. In field corn, stem storage carbohydrates increase during early grain fill, and can be remobilized to be deposited in grain. However, processes occur in the plant before grain fill that could affect sugar transport. For example, stalk internode senescence spreads rapidly at anthesis in

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both field and sweet corn (Russo *et al.* 1998).

Among the desirable quality traits essential for commercial production of fresh or processed sweet corn, kernel sugar content is universally important. Current estimates for the US state that approximately 40% of acreage is composed of *shrunken-2* (*sh2*) genotypes while the remaining 60% is a combination of *su1* and *su1*, *se1* (*sugary enhancer*) genotypes (Schultz and Juvik 2004).

Sweet corn hybrids grown in the United States are traditionally homozygous for the recessive allele *sugary* (*su1*). Hybrids homozygous for the *sh2* allele or homozygous for the *su1* and *se1*genes are also cultivated in temperate areas. The *su1* varieties are more appropriate in places where spring is cold and wet, such as the European Atlantic coast, since they have better germination characteristics than the *su1*, *se1* and *sh2* varieties and show more early vigor (Douglass *et al.* 1993). Some of the *su1* inbreeds developed in northwestern Spain (Ordás *et al.* 1994) and their hybrids are well adapted to European Atlantic conditions. Several studies have shown that genetic background (and not just the single genes *su1*, *se1*, or *sh2*) has a major influence on carbohydrate composition and therefore on table quality (Juvic *et al.* 1993). *Sugary enhancer* material is preferable to *sh2* in the short season conditions of western Europe since *sh2* inbred lines are difficult to maintain due to their poor germination and inconsistent field emergence (Ordás *et al.* 2005).

TRANSPLANT SOWING METHOD

An alternative to direct-seeded maize grown under plastic is the transplanting of maize seedlings raised under cover in a nursery. The protected nursery period shortens the growth period in the field and, as a consequence, even late-maturing, high-yielding cultivars may reach grain maturity in time. In North Vietnam (CIMMYT 1989) and northern India (Sharma *et al.* 1989; Khehra *et al.* 1990) yield benefits from transplanting tropical maize have been reported. In Germany and the Netherlands, research on transplanted ‘temperate’ maize cultivars has indicated encouraging results (van der Werf 1993). Research on transplanting machinery for commercial use is also proceeding (Dale and Drennan 1997a).

Spacing uniformity, timing and rate of emergence, and plant population in a corn stand are the most common characteristics used by producers in evaluating planter performance. Mechanisms and maintenance along with planting speed may all influence seed germination and placement and can further affect plant spacing and emergence variability in corn. Such variability may ultimately affect plant growth and grain yield (Liu *et al.* 2004a).

In recent years, the effects of both plant spacing and plant emergence variability have received considerable attention from corn producers and agronomists as they strive to maximize grain yield. In addition to spacing variability, a corn stand may also emerge non-uniformly. A growth stage difference of two leaves or greater between adjacent plants results in the younger plant being barren at the end of the season. Uniform plant height, which is an indication of uniform emergence, is associated with higher yields (Liu *et al.* 2004b). Late-emerging plants within a row must compete for incident solar radiation, moisture, and nutrients with earlier-emerging neighboring plants which are often taller and have a more developed root system. If competition is severe, late-emerging plants may not produce grain and may actually function as weeds in the canopy (Begna *et al.* 2001a).

From germination to emergence the shoot grows in an upward direction by extension of the mesocotyl and the coleoptile. Normally, the coleoptile encloses and protects the leaves until emergence. At emergence, the growth of the mesocotyl and coleoptile ceases and the first leaf breaks through the coleoptile. In deep sowing and wide diurnal temperature fluctuations the leaves break through the coleoptile below the soil level. This reduced seedling emergence as shoot growth is disoriented, and abnormal seedlings develop (Sass 1977). In a field experiment in which seedling emergence was reduced by long-term exposure to low temperature, Miedema (1982) has indicated that about 15% of the non-emerged seedlings showed this abnormal shoot morphology. Leaf extension was affected more by the temperature of the shoot meristematic region than by the root or air temperature.

The use of transplant is the most reliable method to ensure adequate crop establishment of commercial plantings of various high-value vegetable crops. Other advantages include reduced cost over direct seeding when using expensive hybrid seed, improved land use efficiency, extension of a short growing season, and improved early weed control. For some crops, concentration of crop maturity is improved with transplants. In comparison with direct seeding, transplants can also result in greater early yield when prices tend to be higher. Thus, the added cost of transplant is often justifiable.

Transplant production for commercial vegetable growers is a highly competitive industry in which the ability to deliver the specified quantity and quality of transplant at a specified time is critical to customer satisfaction. This is also a highly mechanized industry. Therefore, quick, uniform seedling emergence and rapid, consistent plant growth is essential for efficient commercial transplant production.

There are marked differences in the survival rate of different vegetable species after transplanting, particularly if roots have been damaged, or weather conditions are unfavorable. In his classic work on transplanting, Loomis (1925) established three classes of transplanting easy. A commonly transplanted group, this usually survives the process well includes cabbage, tomato, lettuce, cauliflower and beets. An intermediate group contains celery, eggplant, onions and peppers. The third category comprises species that are difficult to transplant and includes beans, corn, cucumbers and melons. Primarily it is the below-ground characteristics that differentiate these categories. Ease of root replacement correlated well with transplanting survival. Suberization and formation of cutin on the endodermal layer inhibited root formation and reduced water uptake by the roots remaining after transplanting. Species that were difficult to transplant also had a greater amount of suberization (Wien 1997).

Introduction of the mutant gene *sh2* in place of the standard *su* gene in sweet corn leads to 2 to 3 times increased total sugar content at edible maturity; starch levels in *sh2* are reduced compared to *su1* throughout development, but were less vigorous than *su1* under laboratory and field conditions. Traditionally, acceptance of *sh2* hybrids has been limited due to inferior seed quality, germination and field emergence (Hoyt *et al.* 1994; Parera and Cantliffe 1994; Morse 1999).

Poor seed vigor of *sh2* has been related to small endosperms and the higher sugar content for the kernel during seed development also has been associated with an increase in root by pathogens during germination. Leakage of sugars from *sh2* kernels may enhance these seed roots. Seed that leak heavily are most prone to pre-emergence mortality. Permeable corn seeds, as indicated by a high concentration of soluble materials leaching during a soaking period, were more susceptible to emergence failure under cold soil conditions (Wellbaun *et al.* 2001). Conditions which favored high amounts of nutrient exudation generally corresponded with conditions which favored high levels of pathogen spore germination around seeds, leading to seedling decay.

The greater imbibitions rate throughout germination of mature *sh2* seeds as compared with *su1* may be attributed to several factors (Styer and Cantliffe 1983). The small seed size and weight of *sh2* may allow more water to be absorbed per unit area than the larger-seeded *su1*. Small, flat corn seeds had a faster rate of water uptake than large, round seeds during the initial stages of germination. Standard *su1* sweet maize seeds had more starch than *sh2*, resulting in a lower osmotic potential. The higher levels of sugars to starch

Table 1 Effect of direct seeded and transplant on germination percentage and seedling emergence at the transplant stage (14 days from sowing) for two sweet maize mutant hybrids.

Sweet Maize hybrids	Germination (%)				Emergence (%)	
	Day 6°		Day 12°			
	Direct seeded	Transplant	Direct seeded	Transplant	Direct seeded	Transplant
Canner	89.42	76.04	93.53	91.50	75.34 B	82.50 A
Butter Sweet	84.53	77.08	89.72	90.28	75.10 B	80.46 A

Germination data reprinted from **Di Benedetto A, Molinari J, Rattin J** (2006) The effects of transplant in sweet maize (*Zea mays*) II. Container root restriction. *International Journal of Agricultural Research* **1**, 555-563, ©2006, with kind permission from Academic Journals Inc., USA and emergence from unpublished data. Different capital letters indicate statistically differences ($p \leq 0.05$) from Tukey's test between direct seeded and transplant routines.

in *sh2* seeds could create a higher osmotic potential, giving the potential for more water uptake during the initial phase of imbibitions. A greater number of large airspaces between the pericarp and aleurone layer were noted within mature *sh2* seeds. These spaces can allow the pericarp to be broken easily as well as facilitate water movement. The reduced amount of endosperm of mature *sh2* seeds, containing large airspaces and low numbers of tightly packed starch granules, may partly account for the rapid hydration of these seeds. Rapid water movement into *sh2* seeds would result in accelerated hydration of the embryo, increasing the potential for more damage or leakage (Parera *et al.* 1995).

Reorganization of membranes may be interfered with the inrush of water. During development to maturity, *sh2* seeds generally leaked more electrolytes, including carbohydrates, than did *su1*. This leakage declined with maturity as the protective layers of *sh2* and *su1* seeds became thicker and possibly more lignified. Compositional changes during development, such as the increase in starch content in *su1* seeds, may assist in reducing loss of soluble minerals.

Styer and Cantliffe (1983) indicated that seedling emergence in the field from seeds that leak heavily can be seriously reduced; *sh2* seeds emerged poorly in the cold soil test, and have been shown here to leak more electrolytes and other solutes than *su1* seeds throughout development, regardless of the production environment. The result of this leakage could be increased pathogenic attack in the soil. Kernel respiration during the drying process may account for some of the sugar loss, as well as differences in starch contents. As the ears were drying at 30°C, respiration of *sh2* and *su1* kernels with high moisture contents and readily available sugars could increase for a period of time. Starch breakdown could occur and these sugars, together with sugars already present, may be utilized to maintain respiration.

Selection to increase seed weight and the endosperm: embryo weight ratio has improved seed vigor in the high-sugar genotypes for sweet corn. Di Benedetto *et al.* (2006) showed both higher germination percentages and vigor for the standard *sugary* 'Canner' such as the *sh2* 'Butter Sweet' mutant hybrids. On the other hand, **Table 1** indicates that germination rate and emergence would be enhanced when a transplant routine is used.

ROOT RESTRICTION AND TRANSPLANT SOWING ROUTINE

Although Dale and Drennan (1997a) indicated that grain yield was higher and more consistent from transplanted maize compared with direct-seeded field maize, Wellbaum *et al.* (2001) suggested that transplanting sweet corn remains a questionable practice because it increases production costs and often stunts plant development.

Pendleton and Egli (1969) proposed that one explanation for the transplants yielded no more than the early seedlings may lie in their shorter plant height and less leaf surface. It has been indicated (Wellbaum *et al.* 2001) that maize does not transplant well because pruned roots do not branch and root replacement is generally poor compared with crops such as cabbage or tomato. The inability of maize roots to regenerate after transplanting resulted in stunted plants. By the other hand some of our experiments showed that the transplant routine not ever determines stunted plants at the R_3 stage (**Fig. 1**).

Fig. 1 Sweet maize crops from transplant (left) and direct seeded (right) routines at the R_3 stage grown at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m).

The root system of a maize seedling has seminal roots that consist of the radicle or primary root and a variable number of lateral roots that arise adventitiously at the base of the first internode of the stem, just above the scutellar node. The seminal root initials are present in the embryo and are the most important for early growth and establishment.

Wellbaum *et al.* (2001) showed that seminal roots were broken during transplanting as they were pulled from transplant trays or transplanted, because the polystyrene trays were not optimal for corn transplant production. However, Rattin *et al.* (2006) suggest that it was possible to obtain similar or highest yield from sweet maize plants using a transplant method than direct-seeded under optimal environments. The disagreement with previous reports on the effects of the transplant routine would be associated with the use of plug plastic trays instead of the commonly polystyrene trays which would let avoid the damage to root system when seedlings were transplanted (**Fig. 2A**) (Di Benedetto *et al.* 2006).

A limited plug tray volume from sowing gives a vertical root restriction even under a wide water, nutrient and oxygen supply (**Fig. 2B**); the same effect would be seen when higher containers was used (**Fig. 2C-E**). The post-transplant root restriction effects have been previously documented for other species (Di Benedetto and Klasman 2004, 2007).

The decrease in main root length (**Table 2**) is a typical morphological change for mechanically impeded roots, although the fact that post-transplant growth may substantially be reduced due to the limited volume of the cells in which the plants were cultivated during the plant nursery period has been recently reported (Kage *et al.* 2000; Di Benedetto and Klasman 2004, 2007). Suberization and formation of cutin on the endodermal layer inhibited root formation and reduced water uptake by the roots remaining after transplanting. Species that were difficult to transplant also had a greater amount of suberization. However, the con-

Fig. 2 Root system from *sh2* 'Butter Sweet' sweet corn seedling grown at different container sizes. (**A**) transplant stage, (**B**) V_4 stage; (**C**) V_6 stage; (**D**) V_8 stage (container base) and E: V_8 stage. Reprinted from **Di Benedetto A, Molinari J, Rattin J** (2006) The effects of transplant in sweet maize (*Zea mays*) II. Container root restriction. *International Journal of Agricultural Research* **1**, 555-563, ©2006, with kind permission from Academic Journals Inc., USA.

Table 2 Effect of direct seeded and transplant on root length at the transplant stage (14 days from sowing) for two sweet maize mutant hybrids.

Sweet Maize hybrids	Root length (cm plant^{-1})	
	Direct seeded	Transplant
Canner	40.87	25.03
Butter Sweet	37.47	27.71

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tainer root restriction showed from Di Benedetto *et al.* (2006) for the sweet maize mutants tested (*su1* Canner and *sh2* Butter Sweet) would not be the extreme case of mechanical impedance because the commonly root thickness reduction at the transplant stage (**Table 2**) or root suber accumulation could not be found.

The productivity of maize is constrained by the relative plasticity of the response to environmental stresses. Plant plasticity to abiotic stresses has recently been described as being either morphological or phenotypic in character (Vyn and Hooker 2002). The understanding of the response of maize to particular short- and long-term stresses is limited even further by interactions with other stresses in the crop such as the root restriction imposed by small plug cell trays when a transplant routine was used.

Plant roots can sense adverse soil conditions and, via some internal signal, transmit the condition of the soil to extending leaves, with the typically net result of a decrease in leaf elongation rates. A reasonable body of literature exists supporting the theory that such an effect of mechaniccal impedance on roots might control the overall growth rate of plant leaves. However, some authors reject such a first order effect of impedance and insist that any change in leaf growth is due to water stress associated with soil compaction (Young *et al.* 1997).

On the other hand, less total leaf area was found in plants growing from plastic plug trays which showed intact root systems at the transplant stage (Di Benedetto *et al.* 2006). At transplant, sweet corn seedlings showed a well developed root system with white roots and without damage but the plug cell base determined horizontal root growth around it (**Fig. 2A**). Root restriction stress related to a small plug cell volume could be limited biomass accumulation during the vegetative stages. This effect has been indicated for other plants under intensive propagation systems (Di Benedetto and Klasman 2004) although physiological mechanisms are unclear, both synthesis and translocation of hormones such as auxins and cytokinins from root apices would be involved and related to a change in root verticality as a restriction form the plug cell base.

Hormone availability (auxins and cytokinins) synthesized in the root apex and reallocated to shoots would be reduced when the vertical root growth was impeded by the container base. Strong indications that cytokinins are root factors which are transported via the xylem to the shoots, were they exert a major regulatory influence on growth; photosynthesis and timing of senescence would be available. Root cytokinins are part of the mechanism by which the shoot/root ratio is regulated (Dodd 2005; Rashotte *et al.* 2005; Araki *et al.* 2007). Similarly, maize roots growing under high mechanical impedance for 5 days contained three times more indole-3-acetic acid (IAA) as compared with roots grown in loose soil. Such a rise in the IAA content was associated with inhibition of extension growth of the seminal roots (Lachno *et al.* 1982).

BIOMASS PRODUCTION

Canopy production and crop development are interrelated, for example flowering in gramineous crops occurs on completion of canopy production (Birch *et al.* 2003). Pendleton and Egli (1969) attributed the lack of yield advantage of transplanted maize over direct-seeded maize to the shortened plant heights, smaller number of leaves and lower leaf area indices of the transplants, which would decrease the available sources for photosynthesis. Higher plants intercept incident radiation by leaves and other green organs, utilize that absorbed radiant energy in photosynthesis, and partition photosynthetic products in the accumulation of plant mass. **Fig. 3** shows that there were no differences in plant height between direct seeded and transplanted plants at the final stage of sweet maize crop growth.

Leaf growth is an important process in crop production systems, characterized by the production rate of new leaves, the total number of leaves produced, and the rate and duration of area emergence for each leaf. Warrinton and Kanemasu (1983) reported on effects of temperature on leaf primordia and ligule appearance rates on corn stalks. In grasses, the expansion or extension of newly emerging leaf material takes place within the whorl of emerging leaf material takes place and is complete for the leaf once the ligule has appeared (Hesketh and Warrington 1989).

Process-oriented studies of leaf development have shown that under non-drought conditions, each leaf as a well-defined growth rate are a function of temperature; a maximum leaf area is a function of the position on the plant (Dwyer and Stewart 1986). Thus, in absence of water stress, leaf area development can be described by relatively simple temperature functions (Dale *et al.* 1980). However, the 'root restriction' stress generated by plug cell determines changes in leaf growth. Although total leaf area decreased for transplanted plants, leaf number decreased too; there were not individual leaf area significant differences (**Appendix 1**; unpublished data) between sowing routines (**Table 3**).

Higher plants intercept incident radiation by leaves and other green organs; utilize that absorbed radiant energy in

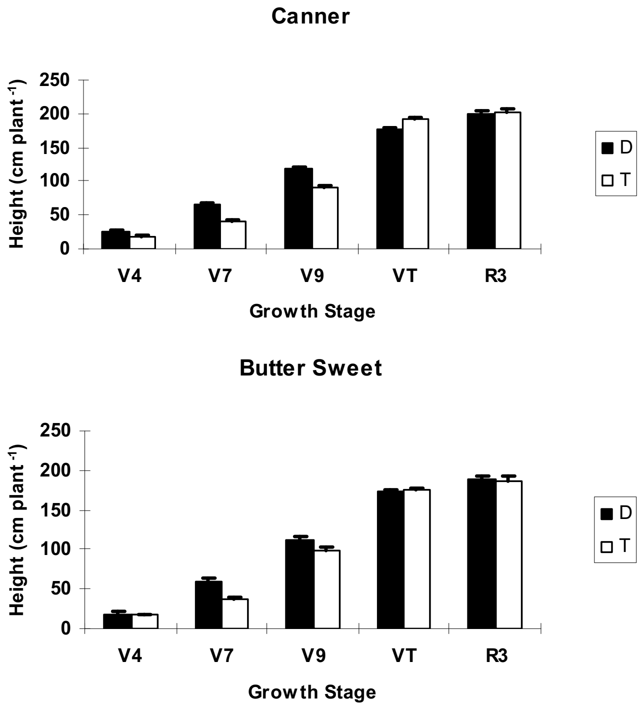

Fig. 3 The effect of direct-seeded (D) and transplant (T) method on plant height for *su1* 'Canner' and *sh2* 'Butter Sweet' sweet maize mutants cropping at 4 plants m^{-2} density. Standard error was indicated. Crops were grown at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m) (**Appendix 1**, unpublished data).

Table 3 Total leaf area (cm^2 plant^{-1}) and leaf number (leaves plant^{-1}) for two sweet maize mutants under direct seeded or transplant at a 4 plants m^{-2} density at the R_3 stage. Crops were grown at the INTA Balcarce Experimental Station, Argentina (37° 45'S, 58° 18'W and altitude 130 m) (**Appendix 1**, unpublished data)

Sweet Maize	**Canner**		**Butter Sweet**	
hybrids	**Direct seeded**	**Transplant**	**Direct seeded**	**Transplant**
Leaf Area	3992 A	3421 B	4201 A	4030 B
Leaf Number	9.88 A	8.55 B	10.00 A	8.75 B

Different capital letters indicate statistically differences ($p \leq 0.05$) from Tukey test between direct seeded and transplant routines.

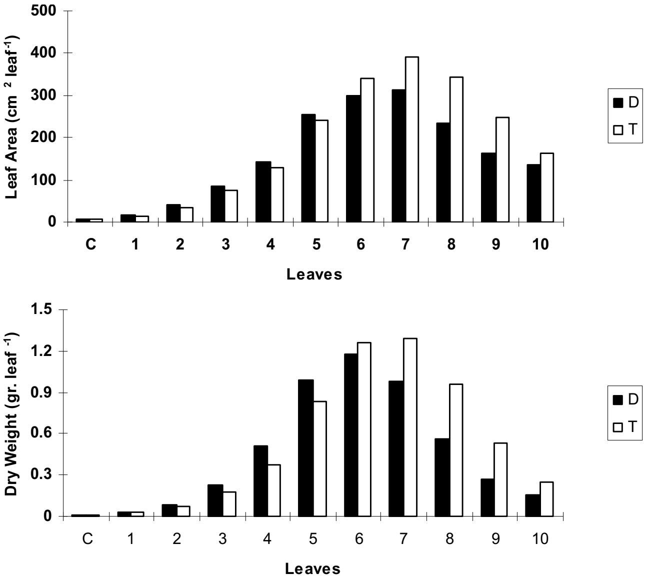

Fig. 4 Leaf Area (cm^2 leaf^{-1}) and Dry Weight (g. leaf^{-1}) from *su1* 'Canner' sweet maize mutant plants initiated through direct-seeded (D) and transplant (T) method. Crops were grown in pots during 6 weeks from sowing (**Appendix 1**, unpublished data).

photosynthesis, and partitioning photosynthetic products in the accumulation of plant mass.

The accumulation of biomass by crops results from the amount of incident photosynthetically active radiation (PAR) intercepted by the canopy, and from the efficiency with which the intercepted PAR is converted into dry matter. The expansion and duration of green leaf area determines the fraction of incident radiation intercepted by the crop. Leaf blades also provide the main path for transpiration and carbon harvesting. In addition, kernel set in cereals such as maize (Andrade *et al.* 2000) has been associated with intercepted radiation around anthesis. Therefore, leaf area strongly influences crop growth and the accurate simulation of green leaf area development during the growing season is a fundamental component of crop growth simulation (Lizaso *et al.* 2003).

In Gramineae species, visible leaf parts are full-grown, because cell division and elongation take place within the sheath bundle. Therefore, the width of leaf parts does not change after emergence of that part. Increase in leaf area of a maize plant can thus be divided into five morphological components: (i) leaf-appearance rate, (ii) leaf-elongation rate, (iii) leaf-elongation duration, (iv) maximum leaf width and (v) leaf-shape parameters. In maize, the effect of temperature on leaf-appearance rate has been studied extensively. Studies on the effects of leaf position and environmental factors on the four other components are, however, relatively scarce. Temperature and photosynthetic photon flux density affect these components in different ways (Bos *et al.* 2000).

An additional factor in identifying optimum leaf area distribution is the relative contribution of assimilates to the grain from different leaves. Assimilates move preferentially from a leaf to its nearest sink. Leaves above and immediately below the primary ear supply most assimilates for grain filling, while assimilates from lower leaves are translocated preferentially to the root and lower stem (Dwyer *et al.* 1992).

The first five leaves of a maize plant are initiated in the embryo before germination, with the first leaf developed to the greatest extent. A large proportion of the growth of these leaves, particularly the first three, is dependent on assimilate from the endosperm and is largely independent of photosynthesis. The large reductions in the area of these first emerged leaves in the 16/6°C environment suggests that assimilate available for leaf expansion was reduced in comparison with higher temperatures. Slow establishment of photosynthesis following emergence at low temperatures may also have contributed to decreased assimilate availability (Hardacre and Turnbull 1986).

On the other hand, direct seeded plants have both higher leaf area and dry weight for the first five expanded leaves but an inverse response for the last five when six week-old plants growing in pots were harvested (**Fig. 4**) (**Appendix 1**, unpublished data).

Because radiation is the key driving force in the ideal growth environment (Sinclair and Muchow 1999), such as ample available water, fertile soil and disease-free for analyzing this, three important indices are summarized next: (i) the fraction of radiation intercepted or light interception, (ii) radiation use efficiency (RUE) and (III) harvest index (HI).

LIGHT INTERCEPTION

Radiation interception varies from seedling emergence to crop harvest and depends largely on the canopy leaf area (Tsubo *et al.* 2001). Leaf area development is described as a function of air temperature. Since temperature affects many plant processes, including nutrient uptake, water absorption, photosynthesis, respiration and translocation of photosynthate, it is not surprising that temperature is considered the most important environmental factor governing plant development.

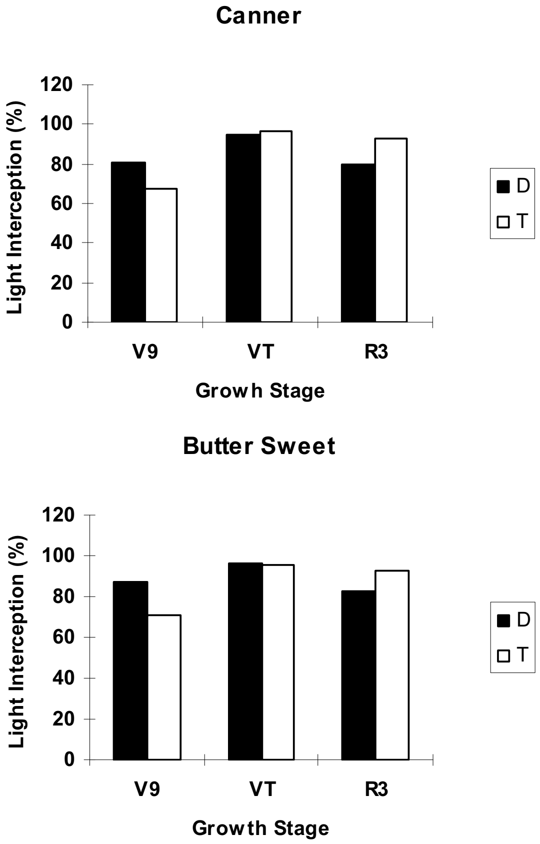

Fig. 5 Light interception from V_9, V_T and R_3 stages for *su1* 'Canner' and *sh2* 'Butter Sweet' sweet maize mutants under direct-seeded (D) or transplant (T) method at a 12 plants m^{-2} plant density. Crops were grown at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m) (**Appendix 1**, unpublished data).

Fig. 6 Picture showed the plant architecture, ear position and ear quality for a *sh2* 'Butter Sweet' sweet maize crop initiated through a transplant routine at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m).

Leaf area is important in determining the percentage of solar radiation intercepted by a plant and it therefore influences plant growth and final yield. Thus, at supraoptimal densities, the efficiency of the crop to convert intercepted photosynthetic active radiation (IPAR) at flowering into grain sink capacity decreases. Intercepted PAR can be used to estimate potential total crop growth because these two variables are linearly related. However, as plant density increase above the optimal density and resources per plant decrease, partitioning to the ear is considerably reduced. A lower leaf area from transplanted plants let to increase plant density; **Fig. 5** showed that critic leaf area index, defined as the plant biomass which let intercept 99% of radiant photosynthetic light, only is achieved during the short period of V_T (pre-anthesis phase) when a high, such as 12 plant m^{-2}, plant density was used.

Since plant growth is a function of light interception, the rate of leaf area establishment after planting is very important to subsequent crop growth. Crop canopy photosynthesis, evapotranspiration, dry matter production and final yield are all influenced by incident solar radiation, through its interception by the leaf surface. The leaf area development phase occurs between seedling emergence and anthesis and is dependent on leaf number, the rate at which leaves are initiated and subsequently appear in the whorl, and the duration of expansion and the expansion rate of individuals leaves (Begna *et al*. 2001b).

Rapid canopy development may be particularly critical in relatively cool, short growing season environments. Besides increasing the plant population to increase leaf area, there have been other specific approaches to increasing assimilate supply in corn crops, especially for short growing season environments. Between the possible alternatives there are to select genotypes with high rates of photosynthesis per unit leaf area, to select genotypes with high rates of leaf area production during the pre-silking phase and to use a transplant sowing routine at high plant densities (Rattin *et al*. 2006, 2008).

Leaf Area Index (LAI) and distribution of leaf area within a corn canopy are major factors determining total light interception, which affects photosynthesis, transpiration, and dry matter accumulation. Vertical distribution of leaf area is determined by leaf size, leaf angle, and internode length. The concept of an ideotype or an optimum plant type for photosynthesis, growth, and grain yield has been introduced. Mock and Pearce (1975) defined an ideotype of corn with an LAI >4 as one with stiff vertically oriented leaves above the ear and horizontally oriented leaves below the ear to maximize light interception by the entire canopy.

Greater light penetration to the ear level of the canopy may confer a significant yield advantage to lines with an LAI above the ear ≤ 3. The importance of leaves in the vicinity of the ear to plant photosynthesis has been demonstrated. These leaves have the highest photosynthetic rates in the canopy and its senesce more slowly than all other leaves, maintaining a high photosynthetic rate into the grain filling period. Leaves in the vicinity of the ear also supply most of assimilates during grain filling; the proximity of the ear sink may even be a factor in maintaining the photosynthetic rate of nearby leaves. However, leaves above the ear are the most recently expanded and therefore also have high photosynthetic rates during grain filling. Dwyer *et al*. (1992) hypothesize that in early maturing lines with a small total LAI, ears are positioned lower in the canopy and the relative proportion of LAI above the ear is increased to maximize the leaf area capable of high photosynthetic rates. In late-maturing lines with high total LAI, ears are positioned higher on the stalk to reduce the proportion of LAI above the ear. This suggests that additional actively photosynthesizing leaf area above the ear in these lines does not compensate for the reduction in photosynthesis at the ear level caused by shading from additional leaf area. The use of a transplant routine resulted in fewer leaves over the ear but with higher individual leaf area (**Fig. 6**).

Plant-to-plant variability may be described in terms of its pattern and its magnitude. Studies of the pattern of variability among individual plants grown as monocultures have indicated that the distribution of dry weight per plant was usually positively skewed (i.e. distributions had a pronounced tail to the right) and that positive skewness increased with time from sowing and with planting density. In contrast, grain yield per plant of field-grown maize was normally distributed and tended towards negative skewness as density increased. It has been demonstrated that exponential growth of seedlings could give rise to positively skewed weight distributions at any given time if times of emergence or relative seedling growth rates were normally distributed. A second important observation on the pattern of plant-to-plant variability is that plant heights were normally distributed. Vegetative organs, which accumulate a proportion of their final size before interplant competition for radiation commences, should be less variable in size than ears and tassels, which are initiated and grow to maturity under conditions of competition for radiation (Edmeades and Daynard 1979). By the other hand, a transplant routine decrease plant-to-plant variability and give a more homogeneous maize crop that direct seeded plants (Rattin *et al.* 2008).

RADIATION USE EFFICIENCY

Shoot Dry Weight production of any crop is strongly correlated to the amount of IPAR by its canopy. The slope of this relationship, called radiation use efficiency (RUE), is often assumed to be very constant within each cultivated species. Many authors have suggested that RUE was relatively stable over a range of environmental and management variables. Kiniry *et al.* (1989) concluded that variability in maize RUE did not appear to be related to differences in temperature in the range of 20-25°C. However, Andrade *et al.* (1992) speculated that the low values of RUE (vegetative period) they found, relative to those presented by other authors, were explained by low average temperatures (15-18°C). In this work, it was demonstrated that RUE during the vegetative period progressively decreased with each temperature decrease below 20°C resulting from early plantings or cool years. Negative effects of low temperatures on leaf photosynthesis, leaf expansion rate, net assimilation rate and relative growth rate were reported for maize. This information supports the concept of a negative effect of cool temperature on RUE (Andrade *et al.* 1993).

On the other hand, experiments conduced at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m; **Appendix 1**), showed that RUE were higher for transplants than for direct-seeded plants when Canner, a *su1* hybrid and Butter Sweet (*shu2* hybrid) were tested (**Fig. 7**) (unpublished data).

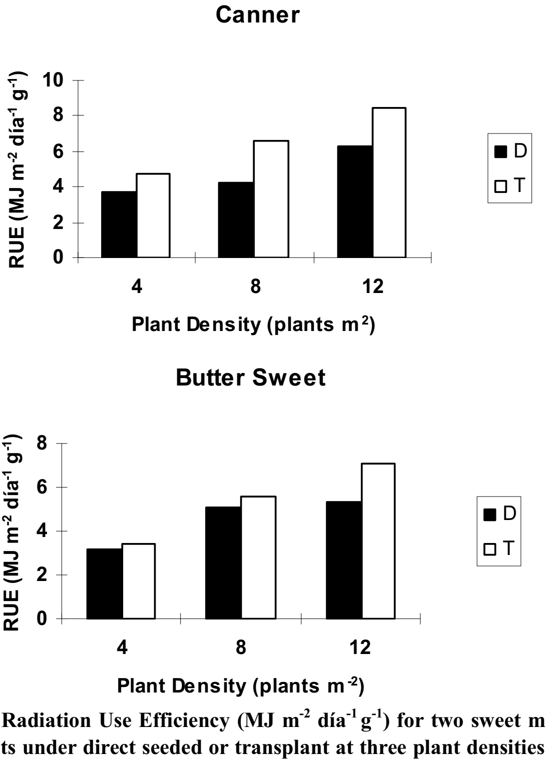

Fig. 7 Radiation Use Efficiency (MJ m^{-2} día^{-1} g^{-1}) for two sweet maize mutants under direct seeded or transplant at three plant densities (D) (4, 8 and 12 plants m^{-2}). Crops were grown at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m) (**Appendix 1**, unpublished data).

DRY WEIGHT ACCUMULATION

Biomass accumulation and partitioning to reproductive structures are critical aspects of plant fitness (Andrade *et al.* 1999). In many plant species, dry matter partitioning to reproductive organs is a stable and highly heritable trait. The mechanisms underlying reproductive partitioning of dry matter between vegetative and reproductive structures. The effect of an increase in plant density radiation on dry matter partitioning between vegetative and reproductive structures are expected (Andrade *et al.* 1993). Rattin *et al.* (2006) showed that a 'root restriction' (transplant treatment) for sweet maize mutants would change photoassimilate partitioning at behalf to reproductive structures (**Figs. 8, 9**) even at higher plant densities (8 plants m^{-2}) than the usually suggested for this crop (4-6 plants m^{-2}).

Dry-matter production is related to light interception and RUE. This simple physiological approach, together with the concepts of photoassimilate partitioning, can be used to predict and analyze crop growth and yield. Of the two components of dry-matter production, light interception has received more attention. It has been mentioned that much of the impact of water supply and nitrogen fertilizer on crop growth was via light interception; moreover, the accumulation of dry matter was more closely related to the amount of radiation absorbed by the wheat crop than to RUE, which was relatively stable.

HARVEST INDEX

Harvest Index (HI), the ratio of grain yield to total plant mass, has been taken as a measure of success in partitioning assimilated photosynthate to harvestable product (Sinclair 1998). Harvest Index or grain weight divided by total shoot weight, is considered stable for maize grown in absence of environmental constraint. Nevertheless, modifications introduced by genotype and stages of growth as a ratio of grain to biomass yield, the HI of cereal crops can be affected by any factor which influences the components of yield to different extents.

Increases in grain yield in maize hybrids have resulted from increased dry matter accumulation because the HI has largely remained constant between 0.49 and 0.51 (Liu *et al.* 2004b; Ding *et al.* 2005). Increased plant population density also tends to result in lower HI, but within the normal range of commercial crop densities, such reductions rarely exceed 10% of the optimum value (Hay 1995). Our previous results are not in agreement and showed that although dry weight ear accumulation are around 40-50%, the transplant routine and the higher plant density increased HI and RUE (**Figs. 8, 9**). These changes would be explained for the lesser shoot dry weight accumulation.

Jepson and Crookston (1986) who showed that an early leaves clipping increased harvest index. A clear varietal response (greater for *su1* Canner than for *sh2* Butter Sweet maize hybrids) has been found. Clipping of early leaves has been shown to increase HI of maize. In a study with sweet maize, Crockett and Crookston (1980) measured an average 20% increase in HI following early leaf clipping. The increase was found to result from a greater reduction in stove mass than in ear mass (Crockett and Crookston 1981). The

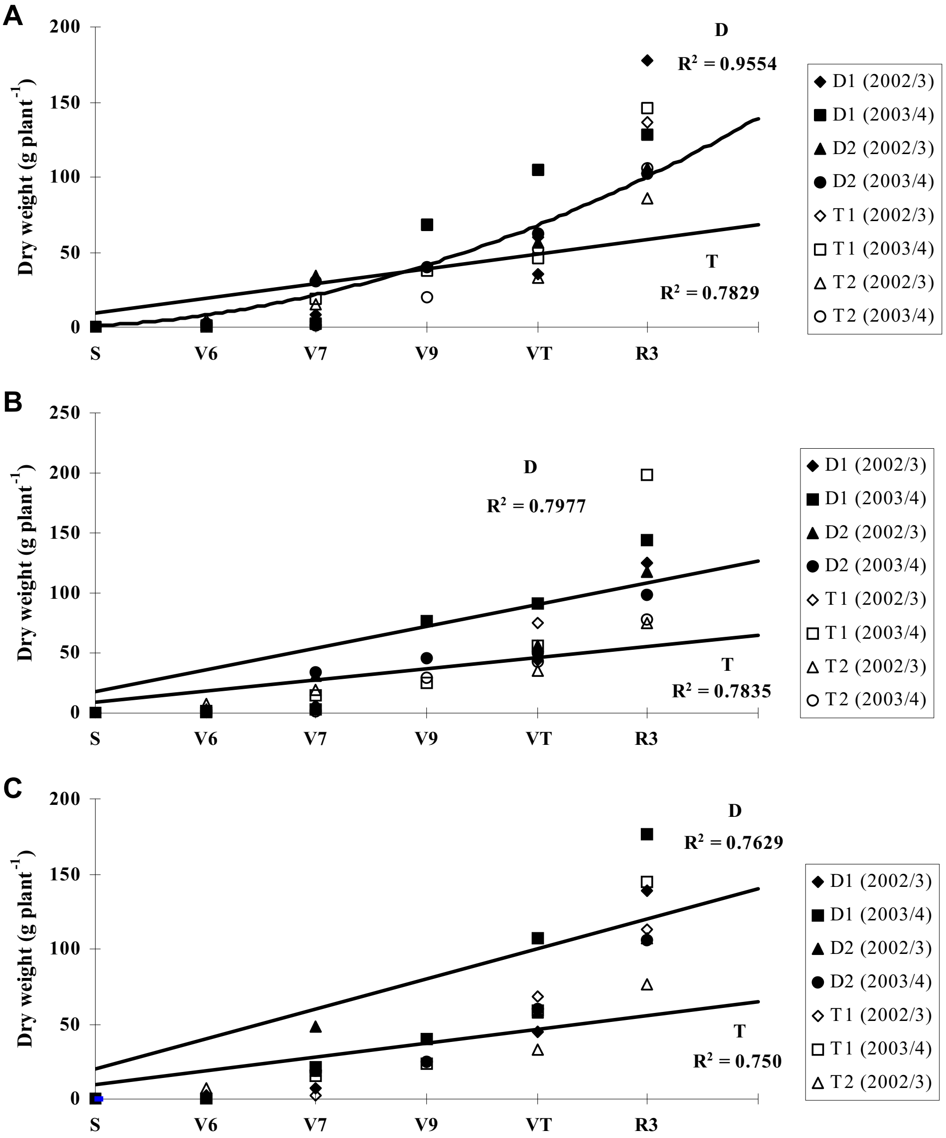

Fig. 8 Dry weight accumulation for *su1* 'Canner' (A), *shu2* 'Butter Sweet' (B) and *se* 'Cheyenne' (C) sweet maize mutants under direct-seeded (D) or transplant (T) method and two sowing dates (1: October, 2: December). Reprinted from **Rattin, J, Di Benedetto A, Gornatti, T** (2006) The effects of transplant in sweet maize (*Zea mays*) I. Growth and yield. *International Journal of Agricultural Research* **1**, 58-67, ©2006, with kind permission from Academic Journals Inc., USA.

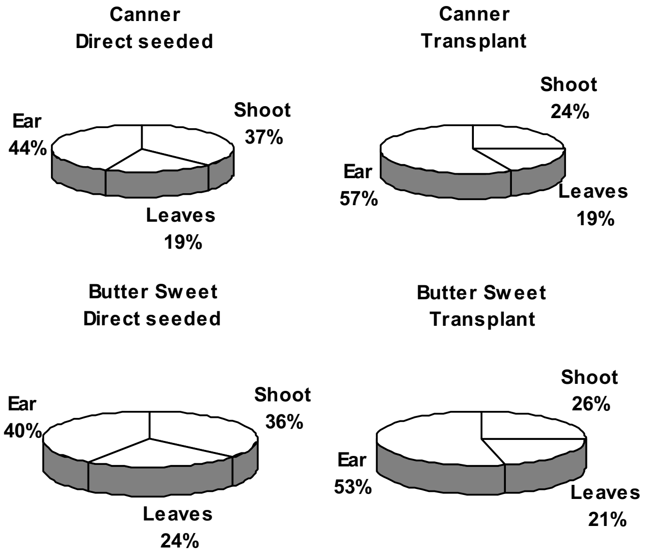

Fig. 9 Dry weight partitioned (gr. plant^{-1}) as Shoot, Leaves and Ear for two sweet maize mutant hybrids cropping under direct seeded or transplant at a 8 plants m^{-2} density. Data are the mean of two years: 2004-2005 and 2006-2007 at the INTA Balcarce Experimental Station, Argentina: 37° 45′ S, 58° 18′ W and altitude 130 m (**Appendix 1**, unpublished data).

results from Rattin *et al.* (2006) are in agreement with these previous results.

Clipping reduces stove because photosynthetic leaf area is removed and vegetative development is retarded, it is possible that early clipping must induce a change in the microclimate of the corn plant, specifically in the temperature of the growing point region. Jepson and Crookston (1986) showed that the growing point temperature of maize was significantly increased by early leaf clipping. The early growing point heating is generally followed by an alteration in the partitioning of dry matter that favored the ear rather than stove. Although transplant determines a decrease in biomass accumulation, mechanism would be different for clipping plants because this treatment commonly decreases yield (Eghareyba *et al.* 1976) and transplant increases it (Rattin *et al.* 2006).

The use of a transplant routine significantly increased harvest index for both sweet maize hybrids and the three plant density tested (**Fig. 10**).

YIELD

Usually grain yield is analyzed in terms of (i) radiation interception, (ii) efficiency of conversion of intercepted radiation into biomass (RUE) and (iii) dry matter partitioning between vegetative and reproductive structures, taking into account the amount of glucose required for synthesis.

Final kernel number in maize is determined by the amount of photosynthate produced by the crop at flowering. The amount of intercepted radiation in that period is critical for kernel set. Ear abortion occurs during flowering, where-

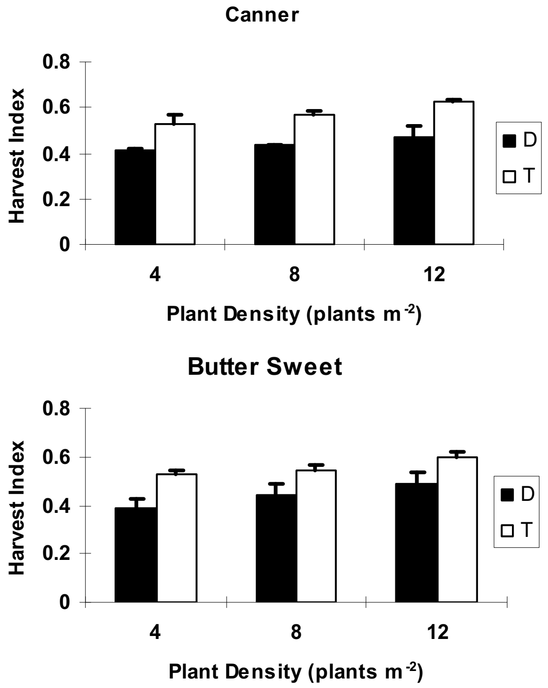

Fig. 10 Harvest Index at the R$_3$ stage for *su1* 'Canner' (A) and *sh2* 'Butter Sweet' (B) sweet maize mutants under direct-seeded (D) or transplant (T) at three plant densities. Standard error is indicated. (**Appendix 1**, unpublished data).

as kernel abortion can continue up to 20 days after pollination. Rattin *et al.* (2008) showed that transplant give no radiation limit during the last phases of crop growth; **Fig. 5** is in agreement with this previous information.

The number of kernel per plant depends on the number of ears per plant and the number of kernels per ear that achieve physiological maturity. The last of these is the component that varies most with environmental changes. Data from **Table 4** showed that there were no differences in kernel number per ear between crop initiation methods; direct-seeded or transplant give similar kernel per row and rows per ear for three maize mutant hybrids. Lower kernel number from transplanted plants was only found for the *se* 'Cheyenne' mutant.

The maize growth stage when kernel number is most susceptible to stress as the period bracketing silking. Thus, the physiological status of the crop at this stage is critical for kernel set. For a specific genotype, the number of kernels set is more critical and more affected by environmental conditions than the total number of differentiated spikelet. Kernel abortion in maize has been linked to a shortage of assimilate supply to developing kernels.

Quantitative relationships between kernel number and intercepted radiation are useful for crop simulation models. The beneficial effects of transplant on yield are related to an increase RUE through a decrease in shading from upper leaves (**Fig. 7**). Total plant growth during the period encompassing flowering is not the only factor that influences the number of reproductive sinks set per plant.

Since most maize genotypes tiller to only a small extent and have low reproductive and foliar plasticity when density is decreased, growth at low densities could be limited by a shortage of sinks (Andrade *et al.* 1993; **Fig. 6**). By the other hand, such a limitation could cause assimilates to accumulate to the point that they depress photosynthesis and consequently RUE (**Fig. 7**), with a greater response when transplant sowing routine was used.

The facts that yield/plant increased with plant density would be partially associated with the use of non-prolific maize hybrids and that a higher plant density increased the tendency to develop a single ear. The negative effect of high density on prolificacy has been attributed to mutual shading at high leaf area indices. Apparently the reduction of light interception limits source capacity, which in turn could retard second-ear growth severely enough for the later to be even totally repressed once the ovules in the apical ear have been fertilized (Sarquis *et al.* 1998). When the dry accumulation changes over time were disagreed in shoots, leaves and ears a clear greater accumulation for ears was seen (**Fig. 9**); the effect was greater for the transplant sowing routine. As dry matter accumulation for maize has been related to PAR interception and RUE; it has been expected that density determine large effects on dry matter partitioning between vegetative and reproductive structures such as the observed from **Fig. 9**. Temporarily-stored soluble carbohydrates in the stem, cob, shank and husks can serve as a source of grain growth when plant photosynthesis declines at the end of the growing season. It seems likely that temporarily-stored soluble carbohydrates can also serve as the source of assimilate for kernel growth when or if plant photosynthesis declines during early stages of the grain-filling period.

Emam (2001) has showed that the most sensitive yield component of maize hybrids to plants population density was the kernel number/ear and sensitivity of kernel number/ear row was slightly less than kernel number/ear. The hypothesis that the lower assimilate supply resulted from reduced light interception at higher densities has been the main reason for abortion of kernels especially at the ear tip is a good explanation for direct-seeded plants kernel number/ear (**Table 5**), but the fact that the period that kernel number/ear row was determined, the competition among sinks for assimilate has been the main limiting factor to kernel number/ear row could be not be true for transplanted plants. By the other hand, kernel row number/ear of non-prolific corn hybrids appeared to be stable in response to increasing plant population density and had a negligible effect in plant yield adjustment. Since the row number of kernel on shoot apex is determined earlier than other yield components (e.g., ear number plant^{-1}), it could be suggested that during that period, the competition among sinks (i.e., florets) for assimilate has not been a considerable limiting fac-

Table 4 Number of kernels per ear, row and number of rows per ear and ear yield (g fresh weight plant^{-1}) for three sweet maize hybrids, *su1* 'Canner', *sh2* 'Butter Sweet' and *se* 'Cheyenne' at direct seeded or transplant.

Sweet Maize hybrids	First Sowing Date					
	Rows per ear		Kernel per row		Kernel per ear	
	Direct seeded	Transplant	Direct seeded	Transplant	Direct seeded	Transplant
Canner	16.7 Aa	16.7 Aa	36.8 Aa	32.0 Aa	616.3 Aa	535.7 Aa
Butter Sweet	14.1 Ab	16.2 Ba	36.6 Aa	30.2 Aa	514.1 Aa	488.8 Aa
Cheyenne	18.0 Aa	16.7 Ba	27.5 Aa	30.3 Aa	495.5 Aa	507.5 A
	Second Sowing Date					
Canner	16.7 Aa	16.0 Aa	26.6 Ab	31.3 Aa	444.6 Ab	503.3 Aa
Butter Sweet	16.0 Aa	16.8 Aa	25.9 Bb	33.2 Aa	413.5 Ab	559.3 Aa
Cheyenne	17.6 Aa	14.7 Ab	28.2 Aa	31.2 Aa	494.9 Aa	454.5 Aa

Capital letters indicate statistically significant differences ($p \leq 0.05$) for hybrids between direct seeded and transplant within sowing dates and lower case letters indicate statistically significant differences ($p \leq 0.05$) among sowing dates for each treatment.

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Table 5 Number of kernels per ear, row and number of rows per ear at R_3 stage for two sweet maize hybrids at direct seeded or transplant under three plant density (D) (4, 8 and 12 plants m^{-2}) (data are the main of two years: 2004-2005 and 2006-2007) (**Appendix 1**, unpublished data).

Sweet Maize hybrids	**Canner**					
	Rows per ear		**Kernel per row**		**Kernel per ear**	
	Direct seeded	**Transplant**	**Direct seeded**	**Transplant**	**Direct seeded**	**Transplant**
D_4	17.1 Aa	16.3 Aa	42.3 Aa	38.7 Aa	719.1 Aa	630.8 Aa
D_8	17.3 Aa	16.3 Aa	30.0 Ab	32.7 Ab	510.3 Ab	533.0 Ab
D_{12}	17.7 Aa	15.7 Aa	29.7 Bb	38.7 Ab	525.7 Ab	607.6 Aa
	Butter Sweet					
D_4	17.0 Aa	16.3 Aa	45.7 Aa	44.0 Aa	776.9 Aa	717.2 Aa
D_8	16.0 Aa	16.6 Aa	45.7 Aa	38.3 Ba	731.2 Aa	612.8 Bb
D_{12}	17.1 Aa	16.7 Aa	36.7 Bb	41.0 Aa	623.9 Ab	684.7 Aa

Capital letters indicate statistically significant differences ($p \leq 0.05$) for hybrids between direct seeded and transplant within each plant density and lower case letters indicate statistically significant differences ($p \leq 0.05$) among plant densities for each treatment.

tor.

Partitioning of dry matter must also be considered. In maize, plant density has important effects on partitioning of dry matter between vegetative and reproductive sinks. At high plant densities, ear and kernel abortion are related to intra-plant competition for assimilates during the flowering period and are probably due to low dry matter partitioning to reproductive structures under these conditions. Moreover, at low plant densities, kernel set in the first ear could be limited by spikelet morphogenesis, which suggests low dry matter partitioning to that reproductive structure during a period bracketing flowering (Andrade *et al*. 1999).

Maize canopy was highly sensitive to plant spatial arrangement. Among canopy components, leaf growth and leaf azimuthal distribution were the traits most affected by treatments. Both processes (i.e., growth and orientation) were affected by plant perception of neighbor shoots before significant mutual shading took place, suggesting that plants have a fast reaction to the light environment. An interaction between hybrid and plant rectangularity on leaf azimuthal distribution was determined, and two types of hybrids, rigid and plastic, could be identified for this trait (Maddonni *et al*. 2001).

In the course of development the architecture of the stand may differ, not only between varieties, also within the same variety, leading to differences in the distribution of radiation within the stand, which in turn may be responsible for differences in productivity indices per unit area. Any alteration in plant architecture influences the energy balance of the canopy. Because of the change in plant density caused by the change in leaf area and its vertical distribution, the radiation properties may have been modified as well (Anda and Loke 2005).

Canopy architecture is a function of plant number, leaf number, shape, distribution, orientation, and plant size, which collectively determine the vertical distribution of light within the corn canopy (Begna *et al*. 2001a). From maize crops initiated by direct seeded, an increased in plant population alone did not compensate for the loss of grain yield caused by decayed plants (Bavec and Bavec 2002). By the other hand, spacing uniformity, timing and rate of emergence, and plant population in a corn stand determine a growth variability that may ultimately affect plant growth and grain yield. Uneven emergence almost always reduces grain yield with early emerged plants unable to compensate for lower yield of late-emerging plants (Liu *et al*. 2004a). Per-plant yield reductions observed for late-emerging plants were associated with height reductions. Whereas plant spacing had no effect on plant height, emergence delays consistently resulted in decreases in maximum plant height. These results suggest that corn plant height is not reduced if plant emergence delay is less than two-leaf stages. Late-emerging plants do not grow as tall as earlier-emerging plants if plant emergence is delayed by four-leaf stages or more. In competition studies, height advantage has been shown to be strongly correlated with ability to intercept radiation and biomass production. Height reductions of late-emerging plants may have resulted from the combined effect of limitations in dry matter available for stem elongation, and by the shortening of phenological stages during which node production occurs (Liu *et al*. 2004b).

The question arises whether a stand with non-uniform plant spacing gives the same yield a uniform stand of the same mean plant population density. The answer may depend on genotype, plant population density, inter-row distance and climate. Field observations show that plants neighboring gaps or bare areas have a higher biomass and produce more grains than plants located in a uniform stand (Pommel *et al*. 2001). Therefore, plants neighboring gaps partially compensate for the missing plants. These plants have more radiation available per unit of leaf area; moreover, they undergo morphological changes that increase their ability to intercept light. The leaves are wider, and the widest leaf has a higher rank. It is important to understand the relative contribution of the amount of available light and morphological adaptation of the plant to increases yield. The latter is due to plant characteristics and, thus, may vary amongst cultivars. It is difficult to assess the intrinsic role of morphological adaptation from field experiments, because plant morphology and light effects are interdependent.

The improved tolerance to high plant populations combined with the low yield potential per plant resulted in modern hybrids that have higher optimum plant population (i.e. population under which maximum crop yield is expected), compared with older ones. Additionally, and more importantly, modern hybrids present a narrow spectrum of optimum plant population. The yield loss due to missing plants would be avoided by increasing the plant population. However, since hybrids are definitely dependent on their optimum plant population, in such a case there is the risk of yield loss because of higher final plant population than the optimum. If the detrimental effects on seed emergence are not fatal, the individual plant may survive, but will be late emerging. Also, differences in sowing depth often lead to a variation in the time of emergence.

Delays in emergence will give differences in plant height and development during the growing season, resulting in a non-uniform stand. When unevenness in plant emergence exists, the intercepted radiation by individual plants will be influenced by the shading from neighboring plants resulting in increased plant-to-plant variability. Actually, high plant populations enlarge plant-to-plant variability. Plant size variability is directly related to neighborhood competition in which the growth of an individual depends on the number, size and proximity of neighbors. As a final impact of increased plant-to-plant variability under high plant populations the grain yield per unit area decreases, because of its association with decreased resource use efficiency (Tokatlidis and Koutroubas 2004). This would not be the case for transplanted sweet maize crops (**Table 6**).

Delayed emergence resulted in less leaf area and dry matter accumulations, high leaf-to-stem ratios, low harvest index, and consequently, those late-emerging plants produced less grain yield than the uniformly emerged plants. In both uniformly and non uniformly spaced stands, yields of plants with a two-leaf or four-leaf stage delay in emergence

Table 6 Ear yield (g fresh weight plant^{-1}) at R_3 stage for two sweet maize hybrids at direct seeded or transplant under three plant density (4, 8 and 12 plants m^{-2})(data are the main of two years: 2004-2005 and 2006-2007) (**Appendix 1**, unpublished data).

Sweet Maize hybrids	**Yield (g fresh weight plant^{-1})**		**Yield (ton fresh weight ha^{-1})**	
	Canner	**Butter Sweet**	**Canner**	**Butter Sweet**
Direct-seeded				
D_4	427.0 Aa	485.7 Aa	12.62 Bb	14.13 Bc
D_8	425.3 Aa	420.8 Ab	26.29 Aa	25.25 Bb
D_{12}	305.7 Ab	339.6 Ac	27.47 Ba	31.61 Ba
Transplant				
D_4	423.6 Aa	515.7 Aa	16.94 Ac	20.63 Ac
D_8	317.3 Bb	364.4 Ab	25.38 Ab	29.15 Ab
D_{12}	322.9 Ab	372.3 Ab	38.75 Aa	44.68 Aa

Capital letters indicate statistically significant differences ($p \leq 0.05$) for hybrids between direct seeded and transplant within each plant density and lower case letters indicate statistically significant differences ($p \leq 0.05$) among plant densities for each treatment.

were decreased by 35 to 47% or 72 to 84%, respectively. This yield decline was never offset by increased yield of its neighbors and always caused a significant total yield decrease in each six-plant unit, regardless of the spacing differences. In this study, the uneven emerging stands yielded less primarily because of the slower rate of plant development in late-emerging plants and the direct competition from their older and larger neighbors. Interactions between within-row plant spacing variability and plant emergence variability on grain yield were significant at the plant level, but not at the canopy level. Reductions in grain yield were attributable to both a reduction in harvest index and a reduction in dry matter accumulation (Liu *et al.* 2004b).

Missing plants in the field are inevitable, where 5-15% of sown seeds normally fail to produce plants. Given that missing plants in the field is a common problem, and the neighboring plants fail to fully compensate for yield of missing plants due to their low yield potential, the final grain yield per unit area decreases. Pommel and Bonhomme (1998) have indicated that when two or three contiguous seedlings were missing, the surrounding plants compensated for 16 and 34%, respectively, of the yield loss due to missing plants. In case of two pairs of missing plants separated by one present plant the increased yield of the surrounding plants compensated for 24% of the yield loss (Tokatlidis and Koutroubas 2004). Our results showed that both effects (missing plants and lesser plant growth rate) could be possible in the short-season area from Balcarce (Argentina) with inadequate minimal temperature when a direct-seeded routine was used and let to explain the beneficial effects of the transplant on emergence rate (**Table 1**) and yield (ton fresh weight ha^{-1}) (**Table 6**).

Increased plant population density, by favoring biomass production over grain, also tends to result in lower harvest index, but within the normal range of commercial crop densities, such reductions rarely exceed 10% of the optimum value (Hay 1995). However, Rattin *et al.* (2006, 2008) and **Fig. 10** showed an increase in HI using a transplant routine although it takes into account that HI for sweet maize included the ear at a R_3 stage.

SOWING DATE

The thermal time requirement for maize to grow to maturity restricts grain production in southern England to marginal areas or exceptionally warm growing seasons, or both (Bunting 1976; Dale and Drennan 1997b). Transplants tend to produce fewer leaves, to flower earlier and thus to benefit from longer grain-filling periods in the field. As a result of their advanced maturity, they give higher harvest indices than direct-seeded plants. Year to year variation in climatic seems to be of primary importance for yield advantages of transplants over direct-seeded maize. The advantage of maize transplanting is therefore likely to be greater in poorer growing seasons.

Maize crops sown in November (South Hemisphere) had less time from emergence to flowering, accumulated more dry matter per unit area at flowering and were taller than those form earlier sowings. The fact that late sowings produced more dry matter at flowering in less time indicates a more pronounced effect of delaying planting date on crop growth than on crop development (Andrade *et al.* 1993).

The success of a transplanting operation depends on the characteristics of the plant being grown and climatic conditions to which it will be exposed after transplanting. Identifying corn hybrids with faster rates of seedling emergence and leaf appearance may allow development of a corn crop that achieves earlier canopy closure and better seasonal light interception. This is very important for short-season areas.

For physiological research, sweet maize plants were harvested at specific stages of vegetative developments as measured by mature leaf number and reproductive stages. Since leaf appearance rate changed with temperature, the time between sowing and each of the increase temperatures during the growing season, which accelerate crop development and decrease accumulated solar radiation (Cirilo and Andrade 1994; Otegui *et al.* 1995) resulting in less biomass production. Rattin *et al.* (2006) indicated that R_3 stage for both direct-seeding and transplanted plants was achieved 7-13 days later, respectively for different sowing dates.

Variation in sowing date in maize modifies the relative and thermal conditions during growth. The amount of incident radiation and the proportion of this radiation that is intercepted by the crop directly determine crop growth rate. Temperature affects the duration of crop growth and consequently the time during which incident radiation can be intercepted and transformed to dry matter. Temperature also affects final leaf number and leaf canopy development which define crop leaf area index. Therefore, these factors determine the proportion of the incident radiation that is intercepted by the crop. Cirilo and Andrade (1994) have indicated that significant differences in crop growth and development would be found when showing date is changed. The same result was found by Rattin *et al.* (2006) for three sweet maize mutant hybrids; late sowing dates would be limited by the assimilation leaf source.

Maize grain yield is closely associated with kernel number at harvest. Therefore, understanding the mechanisms of kernel number determination is of great importance to maize physiologists, modelers, and breeders. In turn, the number of kernels per plant depends on the number of ears per plant and the number of kernels per ear that achieved physiological maturity. The number of kernels per ear is the yield component of maize which varies most with environmental changes. However, unfavorable environmental conditions during ear development can also cause ear abortion. Cirilo and Andrade (1994) showed that kernel number per unit area of crop at harvest was significantly reduced when sowing date was delayed. In conclusion, delays in sowing date affected final kernel number in maize by decreasing the number of ears and number of kernels per ear at harvest. Reductions in crop growth rate after silking determined decreases in the number of kernels set per ear, whereas reductions in number of ears were not associated with crop growth rate in the presilking period, in which an important allocation of assimilates to structural vegetative growth and maintenance respiration in late sowings would be associated with high ear barrenness.

Delayed sowings are generally accompanied by increased temperatures during the growing season, which accelerate crop development and decrease accumulated solar radiation resulting in less biomass production, kernel set, and grain yield (Otegui and Melon 1997). Late-sown maize appears to be limited by the source of assimilates which restricts final kernel size and triggers premature physiological maturity. This provides a possible explanation for the decrease in the sum of thermal units from silking to maturity when sowing was delayed (Cirilo and Andrade 1994). Thus, in absence of drought conditions, the degree-days accumulation methods widely used to estimate maturity in maize would accurately predict time to physiological maturity only when source of assimilates is not limiting.

For the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m) main air temperature are above the thresholds that may affect radiation-use efficiency (16°C) or biomass partitioning to grains (19°C) (Wilson *et al*. 1995) and solar radiation was highest the levels registered in a cool and cloudy high latitude environment of northern Europe (Otegui and Bonhomme 1998). Working at this place we showed that early sowing date was limited by low temperature; during the second sowing date solar radiation and mean air temperature significantly decreased for the kernel-filling stage for both direct-seeded and transplanted crops (Rattin *et al*. 2006).

CONCLUDING REMARKS

According to Loomis and Amthor (1999) who stated that although achieving high yield is conceptually simple (i.e. ‘maximize the extent and duration of radiation interception; use the captured energy in efficient photosynthesis; partition the new assimilates in ways that provide optimal proportions of leaf, stem, root, and reproductive structures; and maintain those at minimum cost’), the processes involved are complex; although transplant would increase harvest index and radiation use efficiency, the precise physiological mechanisms for transplant let unclear and are the subject for following research.

In summary, although there was some differences between the sweet maize hybrids we tested, standard ‘Canner’ (*su1*), *shrunken-2* ‘Butter Sweet’ or *sugary enhanced* ‘Cheyenne’ types, our results let suggest an increase in plant density (12 plants m^{-2}) when transplant sowing routine was included as a tool for increasing yield on an area unit. The economic feasibility for Argentina of transplant when such high density was used showed that the added cost of transplant is often possible (Rattin *et al*. 2008), but the research with different varieties in grower fields are needed to confirm these results and is a theme for future research.

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APPENDIX 1

The experiments were conducted at the INTA Balcarce Experimental Station, Argentina (37° 45′ S, 58° 18′ W and altitude 130 m) during the 2004-2005 and 2006-2007 growing seasons. Maize mutants hybrids Canner (*su1*) and Butter Sweet (*sh2*) Maize mutants hybrids Canner (*su1*) and Butter Sweet (*sh2*) provided by Semillería Basso (Argentina) were shown by direct seeded or in plastic plug trays (128 cells tray^{-1}) using a commercial growing media. Transplanted plants were grown under greenhouse facilities from sowing to transplant. Final population densities were 40,000, 80,000 and 120,000 plants ha^{-1} were shown by direct seeded or in plastic plug trays (128 cells tray^{-1})(Carluccio SRL, Argentine) using a commercial growing media (Fafard Growing Mix 2®). Dry matter accumulation was determined by taking plant samples at stages V_9; V_T and R_3 for the experiments. The sample size was 10 plants per row. Percentage PAR interception was calculated as $[1- (I_t/I_o)]$ x 100, where I_t is incident PAR just above the lowest layer of photosynthetically active leaves, and I_o is incident PAR at the top of the canopy. The values for I_t and I_o were obtained with a LI-COR 188 B radiometer (LI-COR, Inc., Lincoln, EN) connected to a line quantum sensor LI-COR 191 SB. Daily total incident PAR was multiplied by the corresponding daily fraction of PAR interception and accumulated to obtain the PAR intercepted by the crop from sowing to harvest. Radiation use efficiency (RUE) was calculated as dry matter accumulated divided by the intercepted PAR accumulated from V_T to R_3.