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Centre de coopération internationale en recherche agronomique pour le development

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Montpellier, France

Increasing yield potential: lessons learnt from inbreds and hybrids

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Increasing yield potential: past research strategy

- **Selection of New Plant Type was based on 3 main recommendations (Dingkuhn et al 1991):**
  - to reduce non-productive tillers to increase harvest index (also a reason for farmers to transplant old seedlings but then delaying tiller emergence)
  - to increase the sink size of single panicles and ripening period
  - to increase the storage capacity of the stem

- **Crop performance of NPT was finally disappointing (Peng et al 1999):**
  - Low biomass production
  - Poor grain filling (poor harvest index)

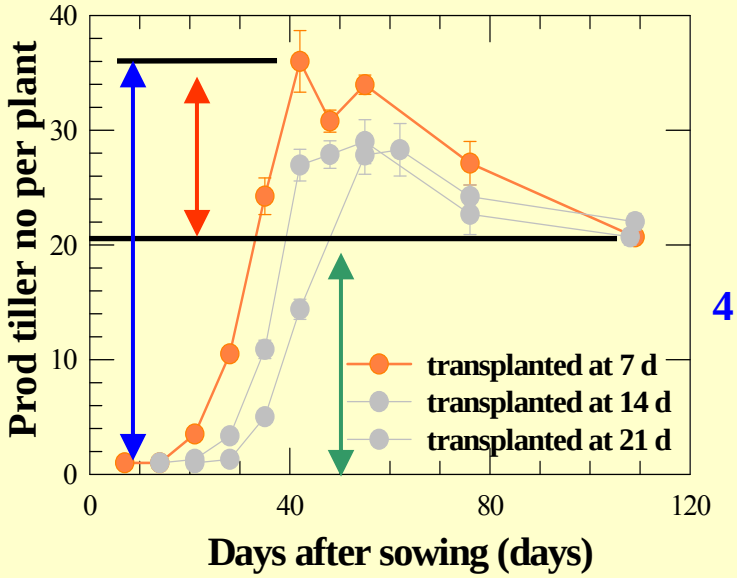
- **Proposed strategies to Increase yield potential:**
  - increasing biomass production rather than harvest index (Khush et al 1998)
  - increasing sink size and biomass production (Ying et al 1998)
  - increasing biomass production rather than harvest index (Peng et al 2000)
  - increasing source strength rather than sink size (Sheehy et al 2001)
  - increasing harvest index rather than biomass production (Yang et al 2007)

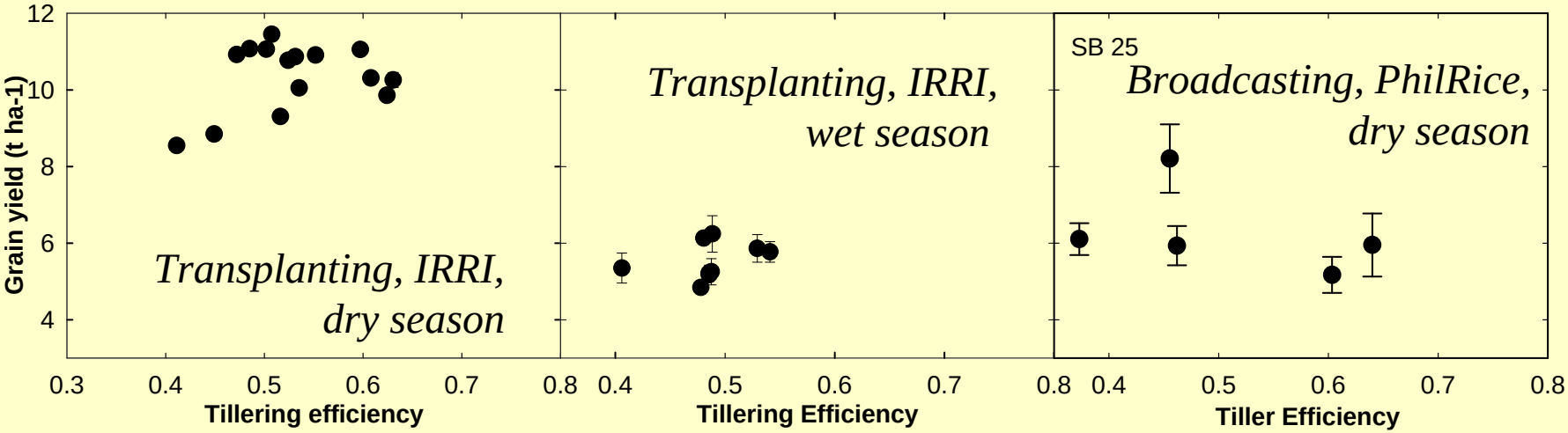
Tillering efficiency: variability across hybrids and inbreds

non-productive tillers

Tillering efficiency (TilE):

$$\text{TilE} = \frac{\text{productive tillers}}{\text{total tillers}}$$





No positive correlation is observed between grain yield and TilE across genotypes in various situations

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High yield: more efficient tiller production?

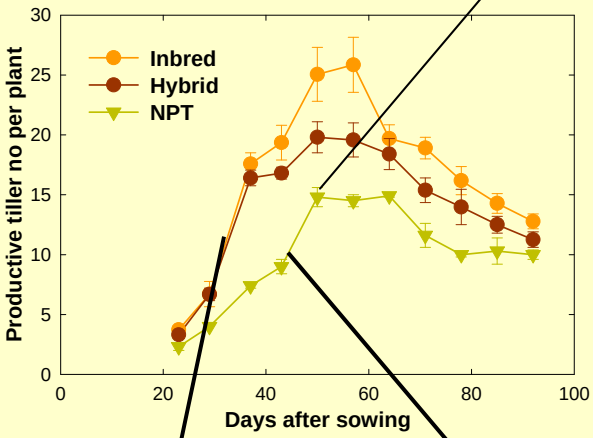
4 inbreds, 4 hybrids and 1 NPT, 2006DS

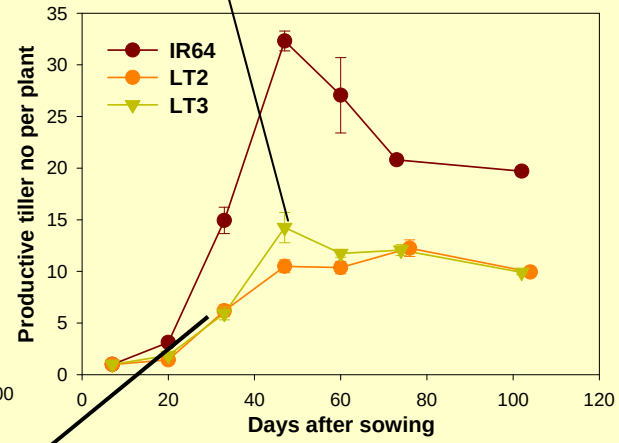
IR64 and 2 low tiller gene introgressed lines with IR64 background, 2004DS

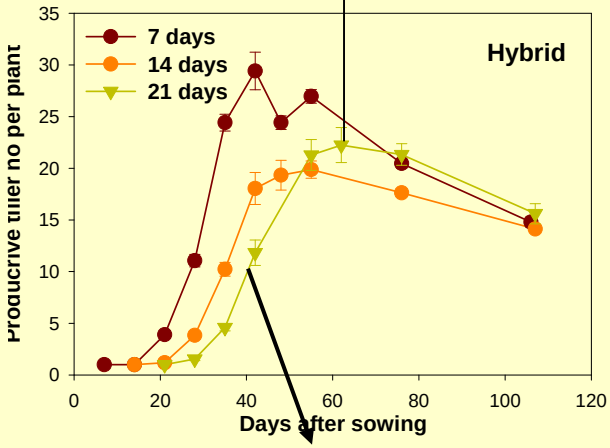
Hybrid rice with contrasting seedling age at transplanting, 2003DS

Similar maximum tillering time

Later maximum tillering







Lower tiller emergence rate

Similar tiller emergence rate

Early and rapid tiller production is already a characteristic of hybrids and inbreds

	GY (t/ha)	TilE
IR64	8.71	0.59
LT2	6.30	0.82
LT3	7.27	0.70

	GY (t/ha)	TilE
7days	7.75	0.50
14 days	6.98	0.68
21days	6.97	0.61

Early and rapid tiller production is essential for high yield

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Hybrid rice: consistently higher grain yield

- **Grain yield advantage: 10 to 15%**
- **Yield components increase:**
  - higher shoot dry weight (Peng et al, 1998, 1999, 2003)
  - higher harvest index (Peng et al, 1998, 1999, 2003; Yang et al, 2007)

Observations from distinct experiments:

higher or similar grain yield and harvest index of hybrid

Significantly-low relation with shoot dry weight but higher values with hybrid

no correlation between grain yield and TilE

HI better related to grain yield than shoot dry matter

Year/ Season		GY (t/ha)	ShDW m^{-2}	HI	TilE
2007 DS	H (7)	11.03 a	2108 a	0.54 a	0.52 a
Transplanting	I (6)	9.48 b	1932 b	0.50 b	0.54 a
2006 DS	H (3)	8.45 a	1780 a	0.51 a	0.56 a
Staggered	I (3)	7.53 b	1634 a	0.45 b	0.55 a
2006 DS	H (2)	8.49 a	1587 a	0.55 a	0.63 a
AWD genotypes	I (3)	8.44 a	1611 a	0.52 b	0.62 a
2005 DS	H (2)	7.16 a	1959 a	0.45 a	0.41 b
Broadcasting	I (2)	5.94 b	1820 a	0.42 a	0.55 a
2004 WS	H (5)	5.93 a	1885 a	0.45 a	0.52 a
Wet season	I (7)	5.35 b	1748 b	0.42 b	0.49 a

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Hybrid rice: yield components of plants with same phenology

Comparing yield components of 3 hybrids and 3 inbreds with the same phenology: similar PI, flowering and maturity time, leaf emergence rate and culm elongation

Gen	GY t ha^{-1}	Pan no m^{-2}	FiGr no pan^{-1}	Grain size	ShDW g m^{-2}	HI	Sink size no m^{-2}	Gr Fill percntage	TilE
H5	11.07 b	329 a	137 b	23.96 d	2303 a	0.55 a	54766 a	0.825 ab	0.62 a
H8	11.06 b	308 b	144 a	24.35 cd	2027 b	0.52 ab	59070 a	0.755 c	0.57 ab
H14	11.45 a	328 a	136 b	25.11 bc	1879 bc	0.54 a	56860 a	0.782 c	0.52 ab
I9	9.30 c	331 a	105 d	26.01 ab	1827 c	0.46 d	43904 b	0.80 abc	0.58 ab
I10	8.55 e	309 b	114 c	23.60 d	1834 c	0.50 bc	42492 b	0.835 a	0.50 b
I12	8.84 d	301 c	108 d	26.55 a	1971 bc	0.51 cd	39294 c	0.830 ab	0.59 ab
Mean-H	11.19 A	322 A	139 A	24.47 A	2070 A	0.54 A	56899 A	0.79 A	0.57 A
Mean-I	8.90 B	314 A	109 B	25.39 A	1877 B	0.49 B	41897 B	0.82 B	0.55 A

H5: IR78386H / H8: 80793H / H14: 82386H / I9: 77958-7-4-3 / I10: 77958-14-4-7 / I12: 76928-74-3-2-1

Hybrid: higher biomass, sink size and harvest index triggered higher filled grain per panicle

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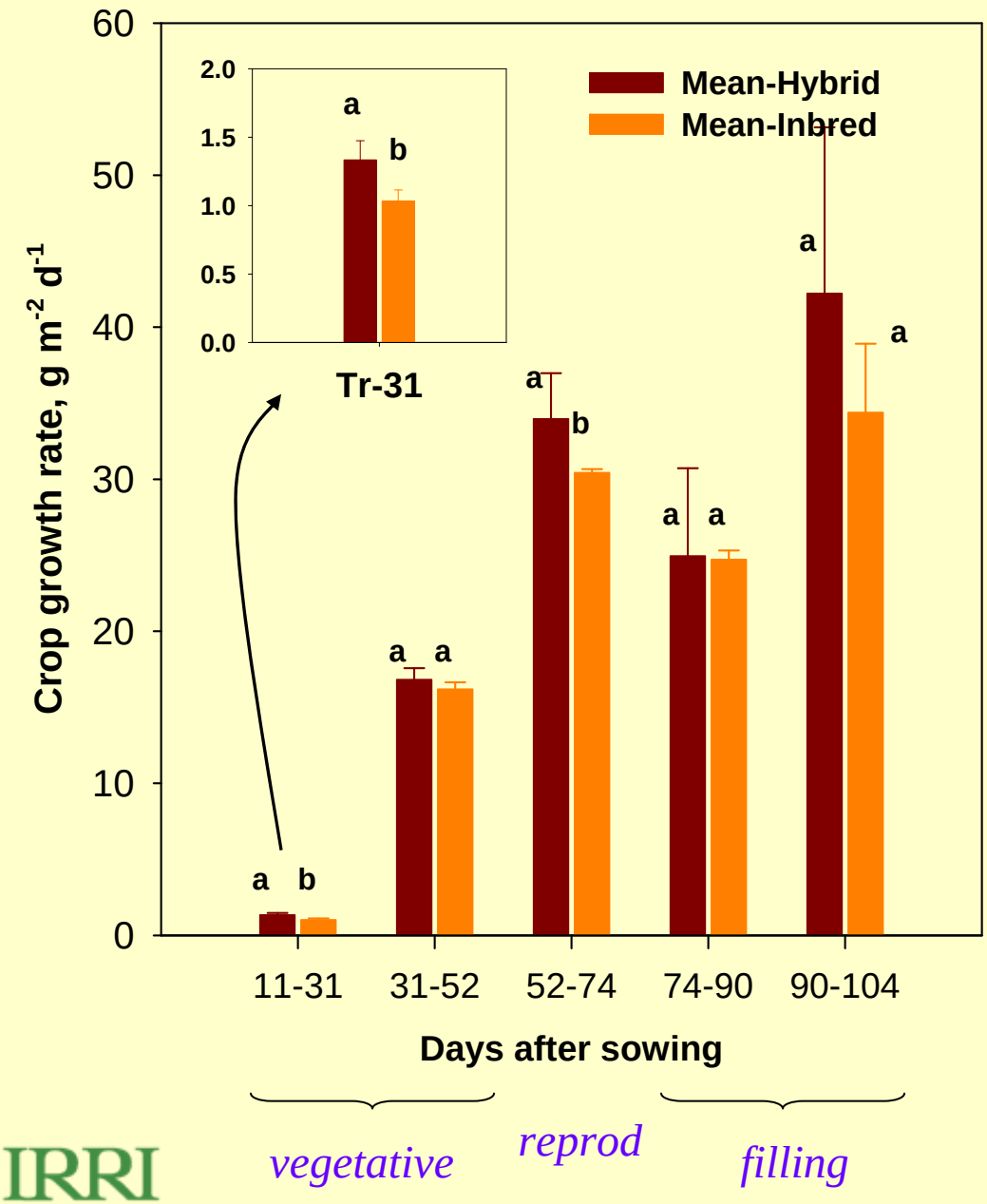
Higher biomass: which phases are involved?



Comparing crop growth rate of hybrids and inbreds of same phenology during the three phases of development

$$CGR = \frac{\Delta dw_{shoot\ 2\rightarrow 1}}{\Delta time_{2\rightarrow 1}}$$

Higher CGR is observed in the 3 phases of development, but this is only significant at very early stage and during culm elongation

Which traits are supporting higher CGR in hybrids?

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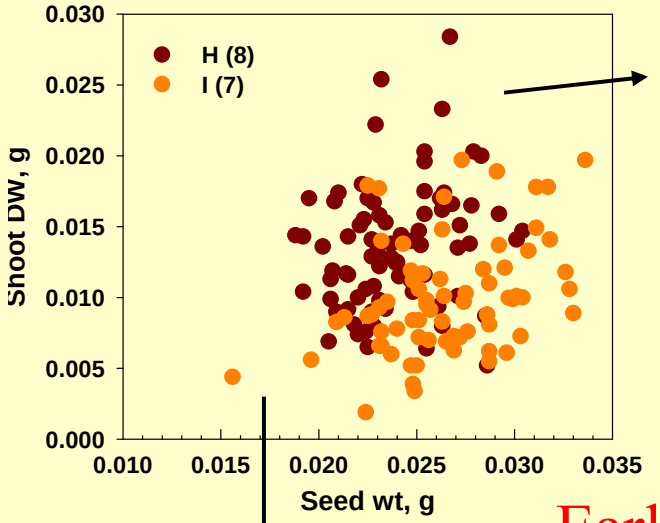
Higher biomass: early hybrid vigor?

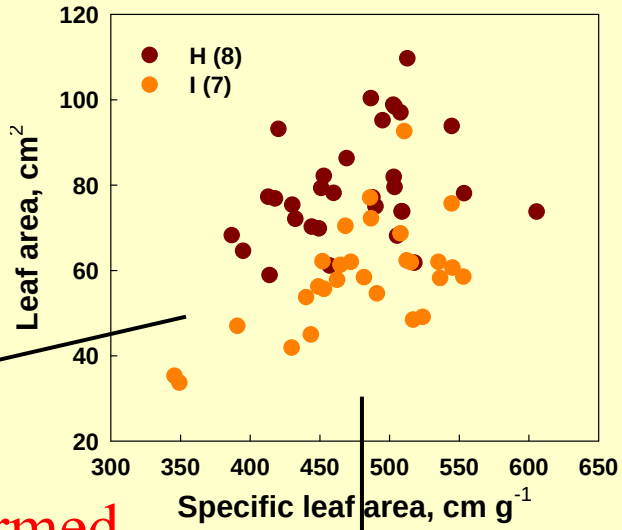
Analyzing correlations at transplanting (15 genotypes, 8 hybrids and 7 inbreds)

Transplanting



Hybrid: higher shoot biomass of the seedling with regard to its individual seed size

Transplanting



Hybrid: higher leaf area of the seedling with regard to its specific leaf area

Early hybrid vigor is confirmed

Seed size and SLA are not the cause of early hybrid vigor. So, what is the cause?

No impact of the individual seed size on individual shoot biomass

But increase in leaf area with higher specific leaf area

Higher SLA can trigger higher seedling vigor (higher leaf area)

⇒ Can plants grow with even higher SLA?

Increase of 50 cm g^{-1} with shading from tillering to booting

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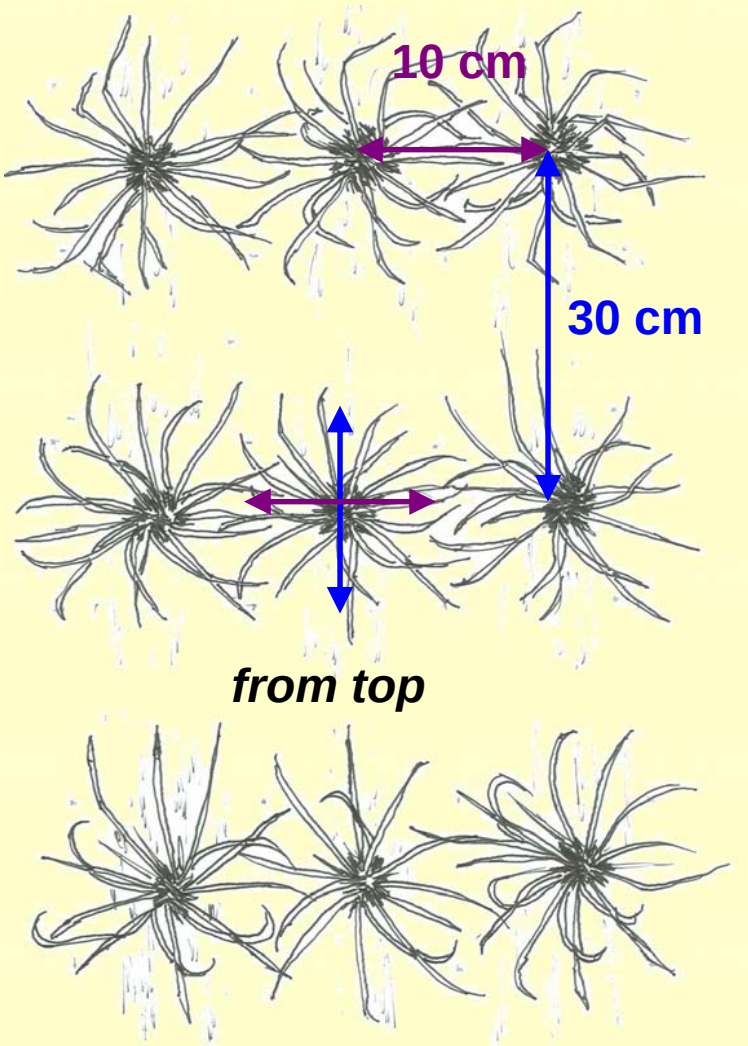
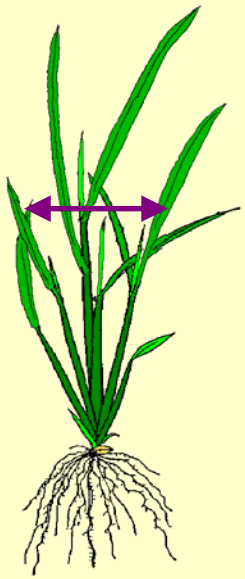
Higher biomass: more efficient plant stand at early stage?

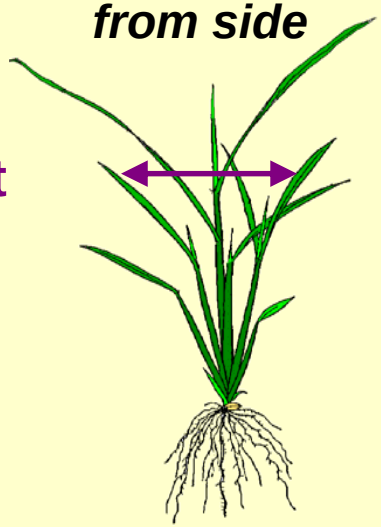


Evaluation of the clump plasticity in a transplanted field with a rectangular spacing 30 x 10 cm



from side

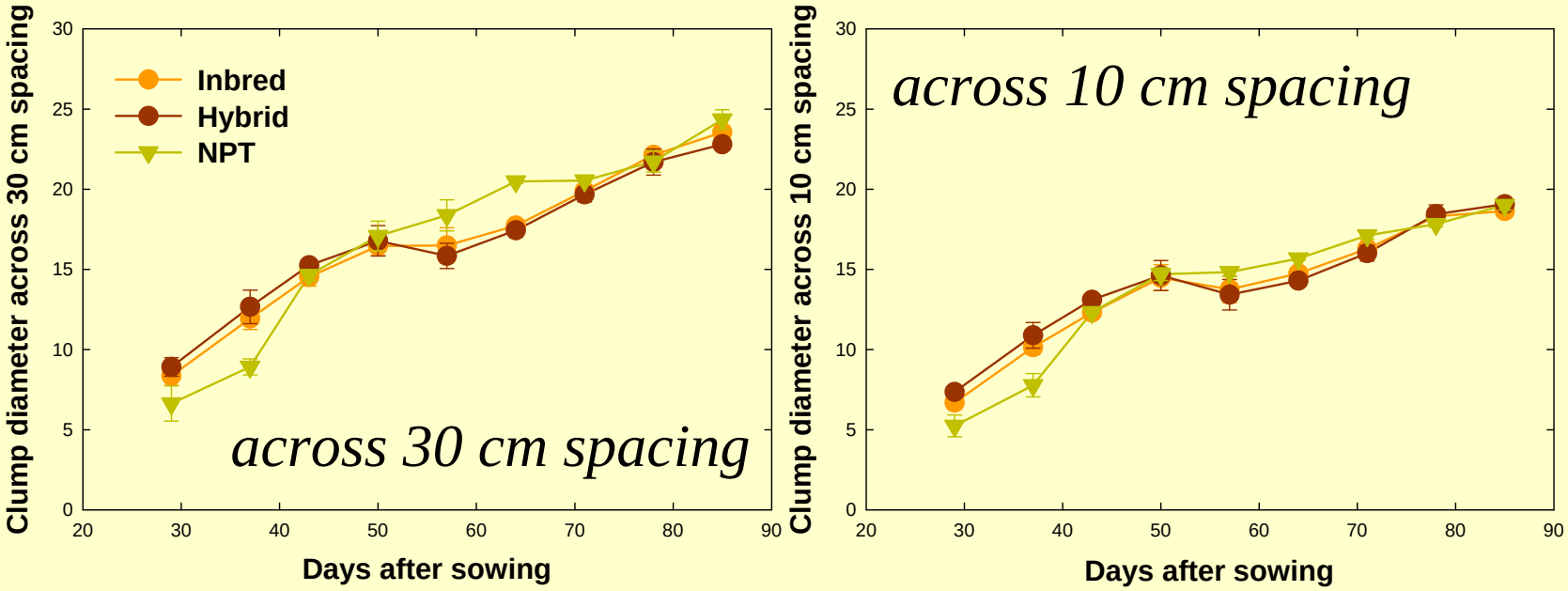
Is the clump diameter in the 30 cm spacing different from that in the 10 cm spacing?



Can plant stand adapt to the surrounding plant distribution?

Higher biomass: more efficient plant stand at early stage?

Comparing the clump plasticity of 4 inbreds and 4 hybrids (both plant types represented as an average) and 1 NPT, all of same leaf emergence rate (same phenology)



Same sensitivity of hybrids and inbreds to intra-plant competition:
similar dynamics is observed of clump size between hybrids and inbreds

Weak sensitivity of hybrids and inbreds to intra-plant competition:
similar dynamics is observed regardless of spaces between plants

Same clump plasticity:
same adaptation to direct-seeding?

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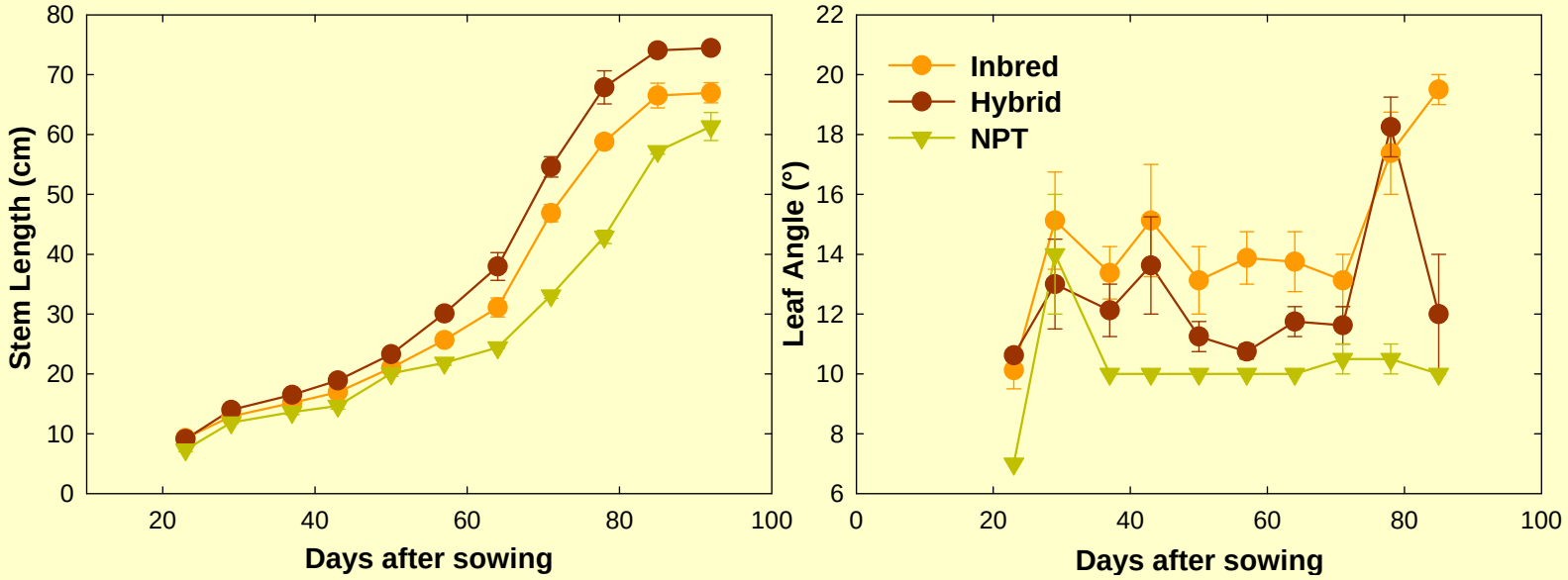
Higher biomass: more efficient plant stand at early stage?

Comparing the plant height and leaf angle of the second youngest mature leaf of 4 inbreds and 4 hybrids (both plant types represented as an average) and 1 NPT, all of same leaf emergence rate (same phenology)



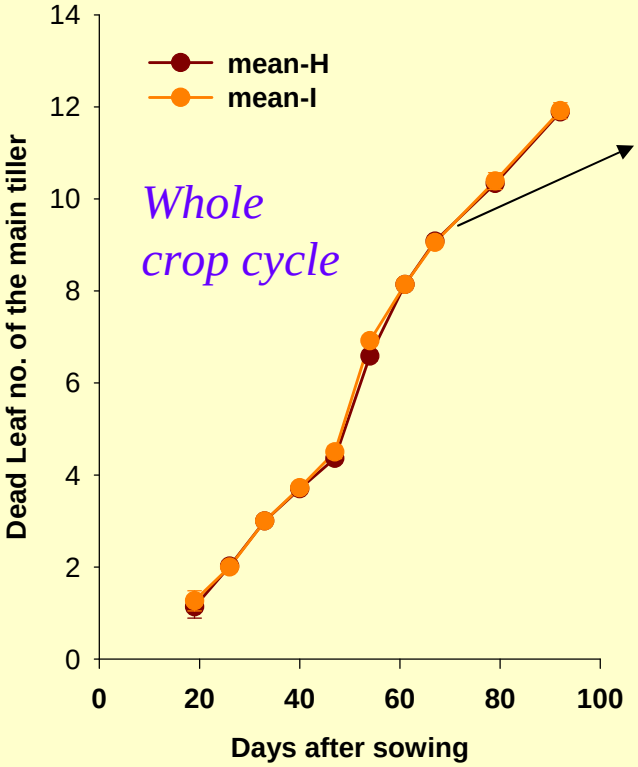
Hybrid: characterized with more erect leaves and taller canopy that may trigger Higher light interception

NPT: characterized with extremely rigid architecture with small canopy and no variation in leaf angle with time

Leaf position and orientation may be candidate traits

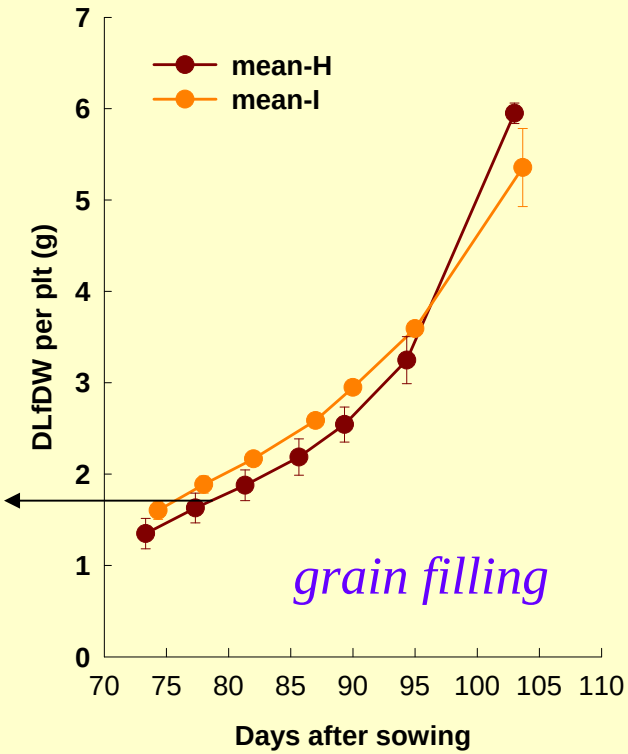
Higher biomass: delayed leaf senescence?

Comparing dynamics of leaf senescence in terms of number and dry matter of 3 hybrids and 3 inbreds with same phenology



No difference in leaf senescence on the main tiller

Hybrid:
- slight delay in leaf senescence at the start of grain filling
- higher sensitivity to the final drainage period?



Is there any variability in root senescence during grain filling and can this have an impact on leaf senescence?

What about remobilization from senescing leaves?

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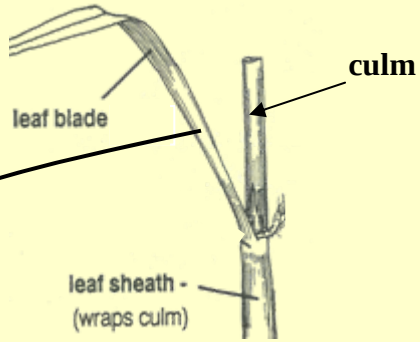
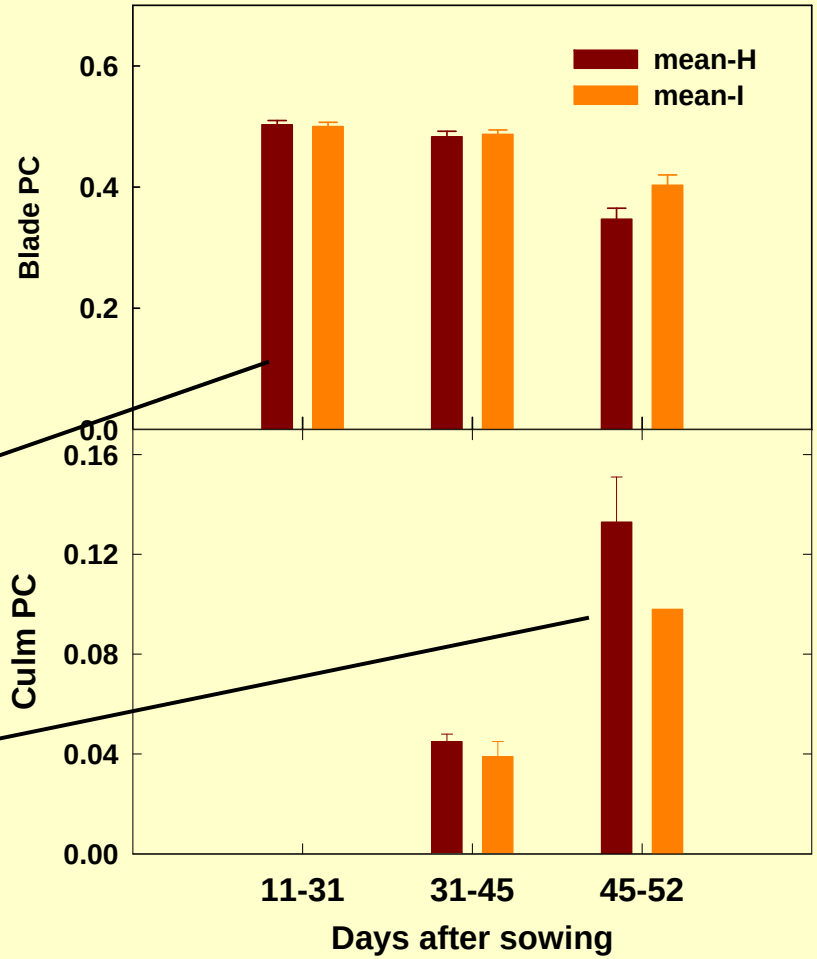
Higher sink size: better sink regulation at early stage?

Comparing partitioning coefficients of 3 hybrids and 3 inbreds of the same phenology

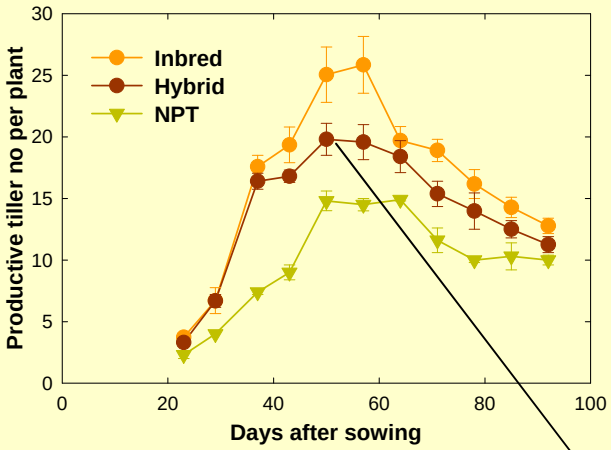


vegetative phase



Calculation of blade partitioning coefficient:

$$\text{Blade PC} = \frac{\Delta dw_{\text{blade } 2\rightarrow 1} / \Delta time_{2\rightarrow 1}}{\Delta dw_{\text{shoot } 2\rightarrow 1} / \Delta time_{2\rightarrow 1}}$$



Similar sink regulation until PI

Hybrid:
- quicker increase in allocation to the culm around PI

Hybrid: earlier cessation in tiller emergence is observed at the time of change in sink regulation in favor to culm

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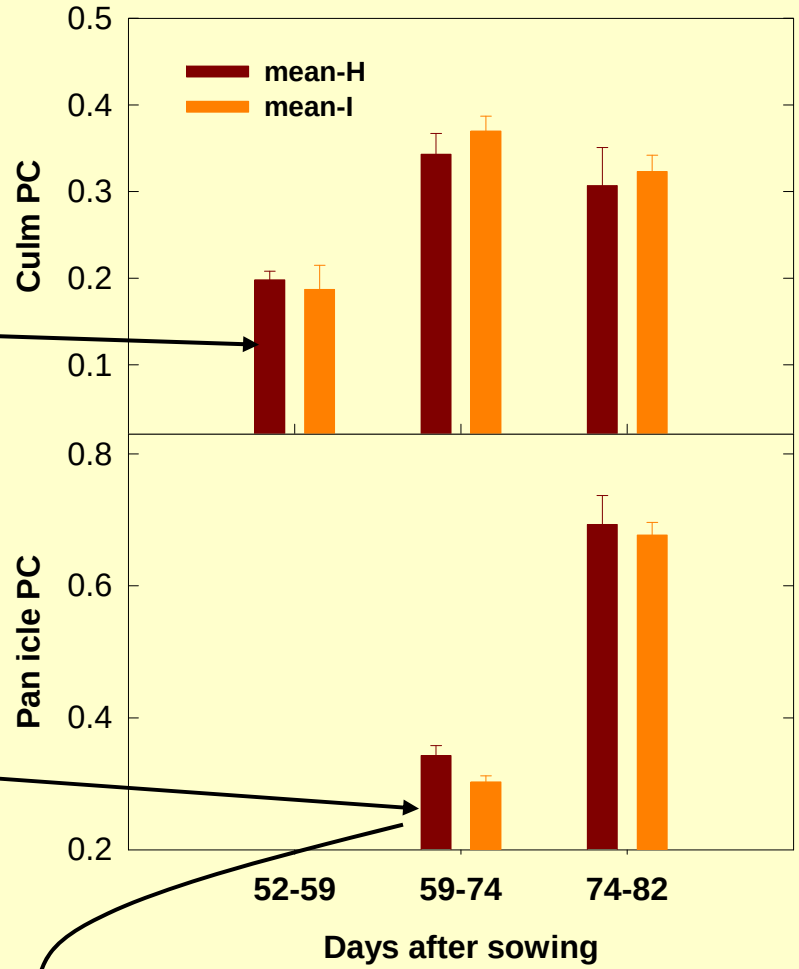
Higher sink size: better sink regulation during culm growth?

Comparing partitioning coefficients of 3 hybrids and 3 inbreds of same phenology

Isolating the culms from leaf blades, sheaths and juvenile panicles

Removing the juvenile panicles enclosed in the leaf sheaths



culm growth

early filling

Hybrid: quicker increase in allocation to the panicle before flowering

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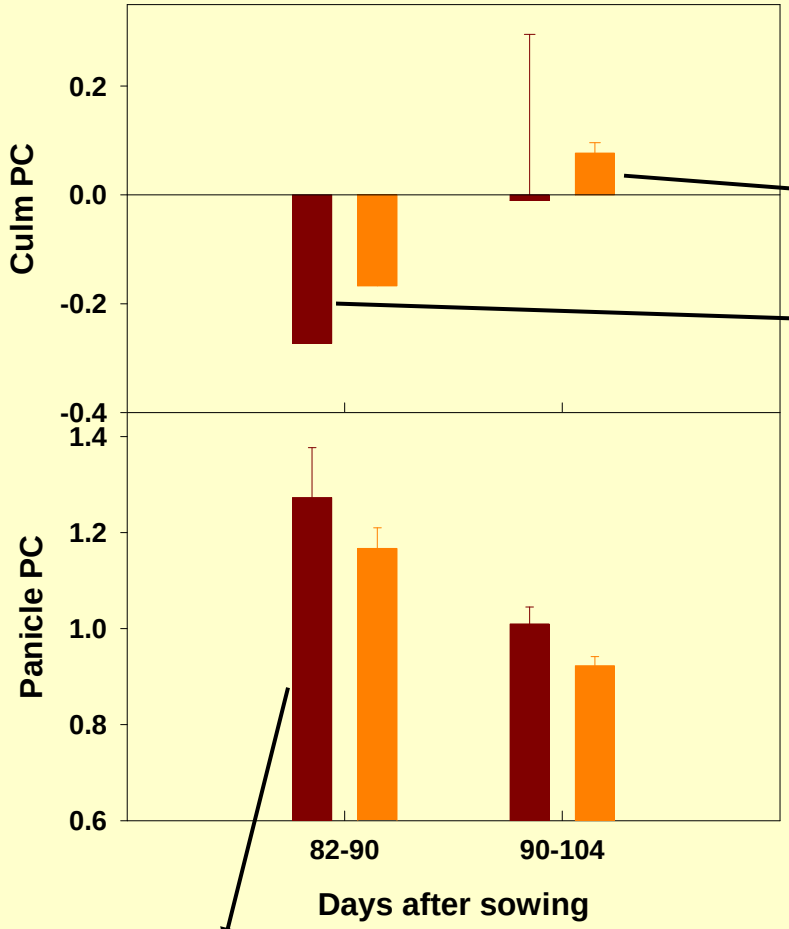
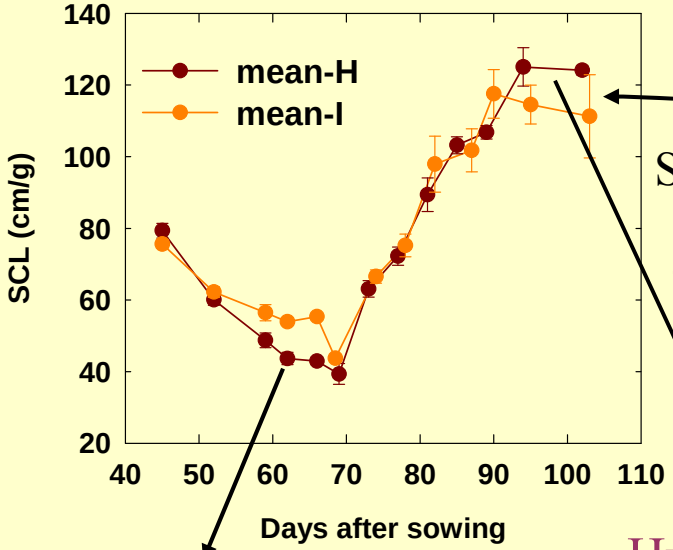
Higher harvest index: better sink regulation during grain filling?

Comparing partitioning coefficients of 3 hybrids and 3 inbreds of same phenology



Inbred: increase in culm biomass at the end of grain filling to bear the panicle

Hybrid: higher remobilization



Specific culm length:

$$SCL = \frac{\text{culm length}}{\text{culm dw}}$$

Hybrid: stronger allocation to the panicle during the whole phase

Hybrid: stronger culm at flowering

Hybrid: weaker culm at maturity

Hybrid: the stronger ability of the culm to store and remobilize biomass is likely to increase grain filling

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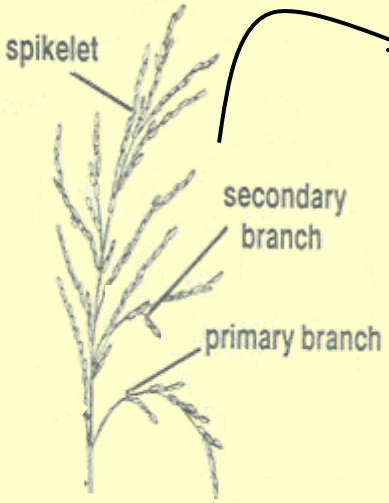
Higher harvest index: better sink regulation during grain filling?



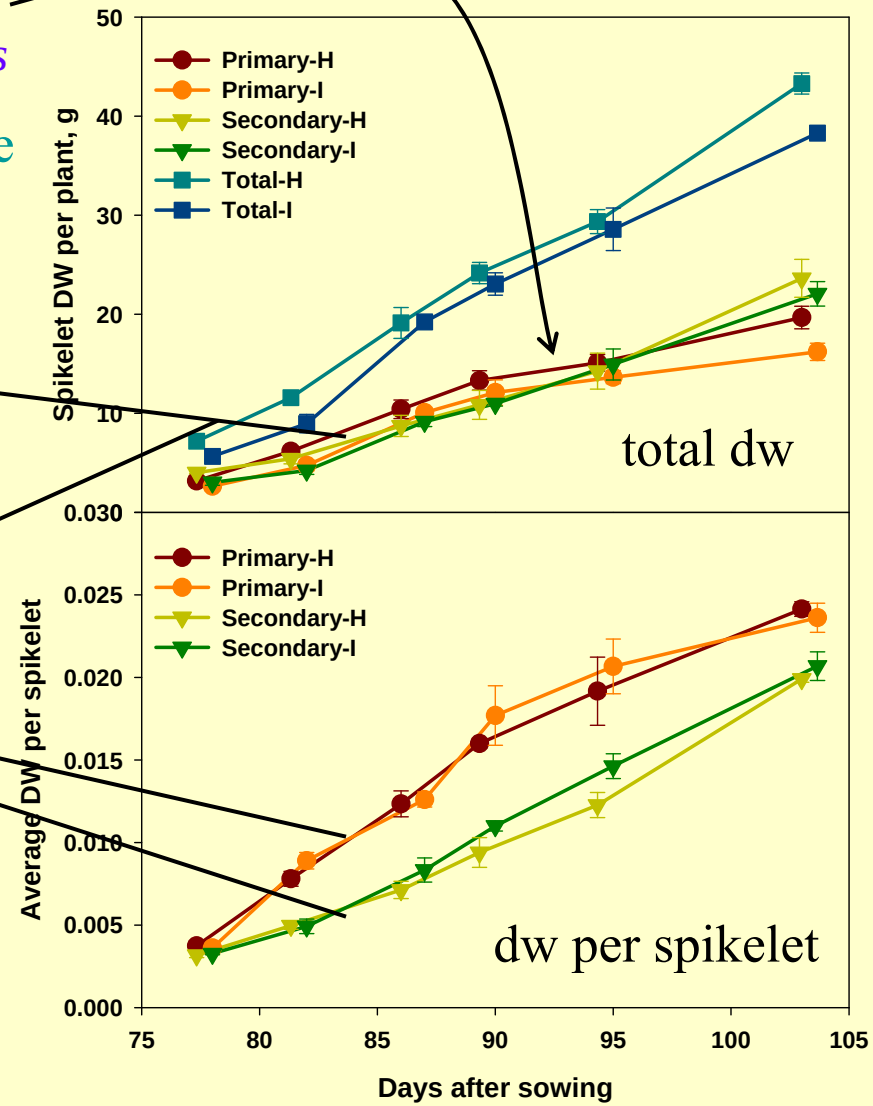
Separation of primary and secondary spikelets

Primary spikelets are filled in priority to secondary spikelets, are heavier during the whole period in both plant types

Hybrid: faster grain filling rate

No difference in individual spikelet dry weight is observed across plant types

Hybrid at early and late filling stage:
- quicker spikelet filling rate
- similar individual spikelet dry weight



Hybrid: more spikelets are filled at the same time

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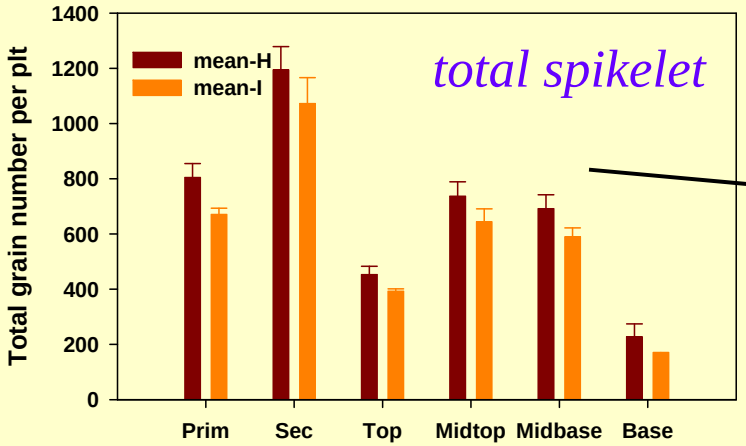
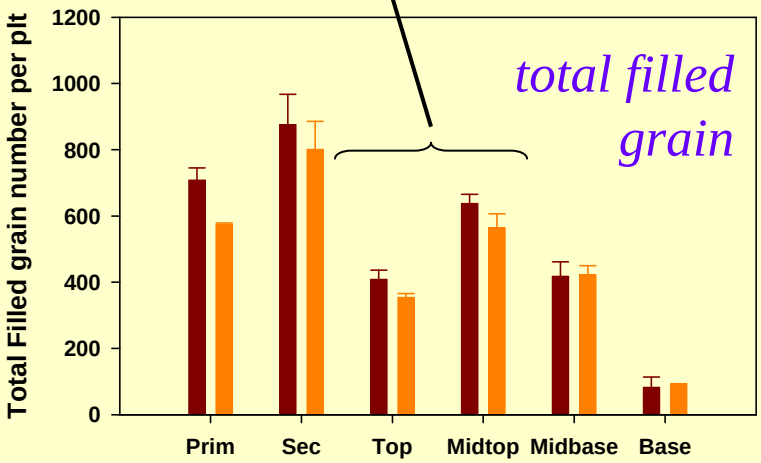
Higher harvest index: better sink regulation during grain filling?

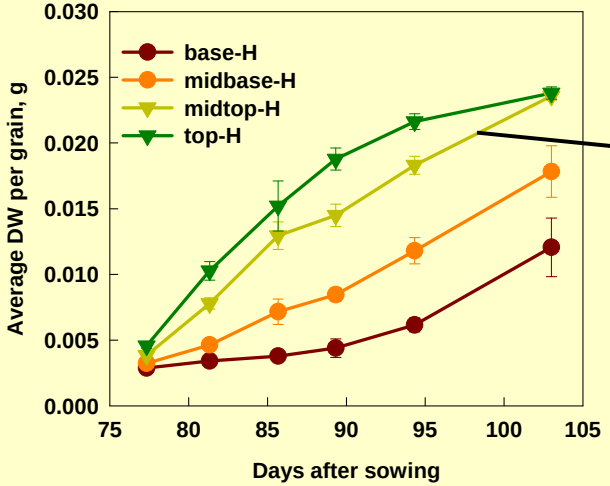
Comparing the pattern of grain filling along the panicle of 3 hybrids and 3 inbreds of same phenology



Hybrid: the sink size is higher along the whole panicle

Hybrid: the difference in filled grain number is observed in the upper part of the panicle





The upper part of the panicle is characterized by spikelet with higher individual sink size than at the base

Hybrid: the superiority in grain filling is expressed during the whole filling period, is visible in the upper part of the panicle where the sink size of individual spikelet is higher

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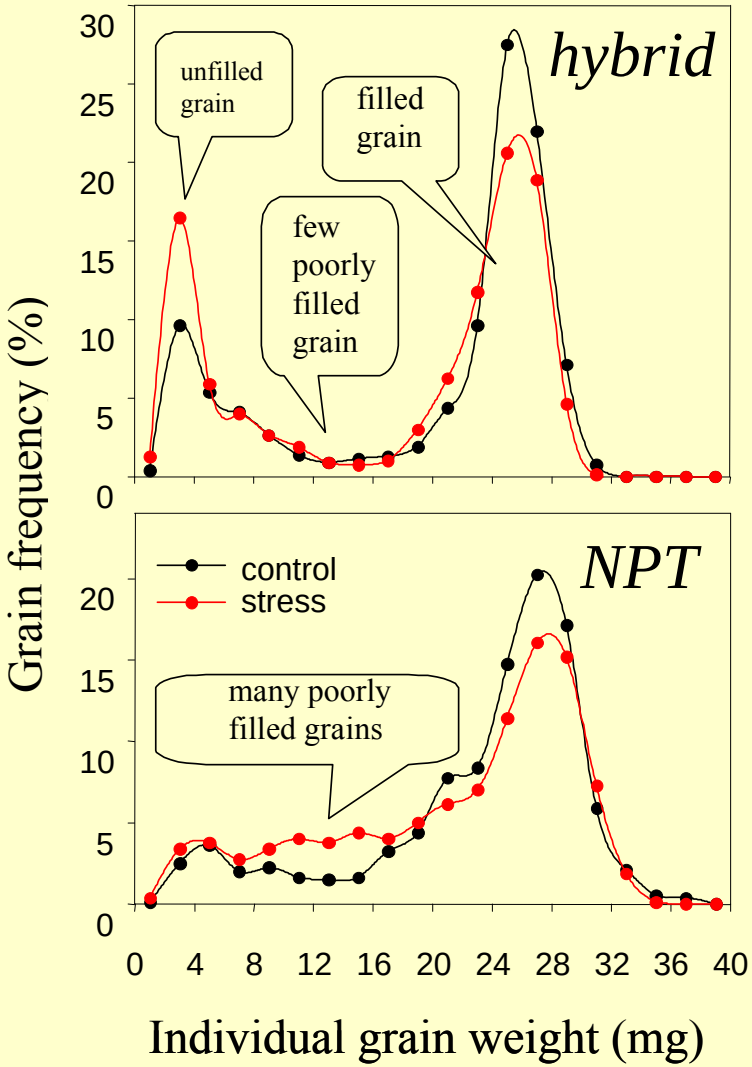
Higher harvest index: better sink regulation during grain filling?

Grain size distribution, PSiband data



Year/ Season	Genotype	1000 FiGrDw	1000 UFiGrDw
2007 DS	H(7)	24.45	4.33
	I(6)	24.40	4.55
2006 DS	H(2)	24.82	5.01
	I(3)	26.84	5.28
2005 WS	H(3)	27.37	4.26
	I(2)	27.00	4.44
2005 DS	H(2)	24.21	4.98
	I(2)	23.41	5.06
2004 WS	H(5)	24.70	4.17
	I(7)	25.23	4.77

Hybrid: grains either filled or unfilled but few poorly filled

Can unfilled grain size be used as a relevant trait?

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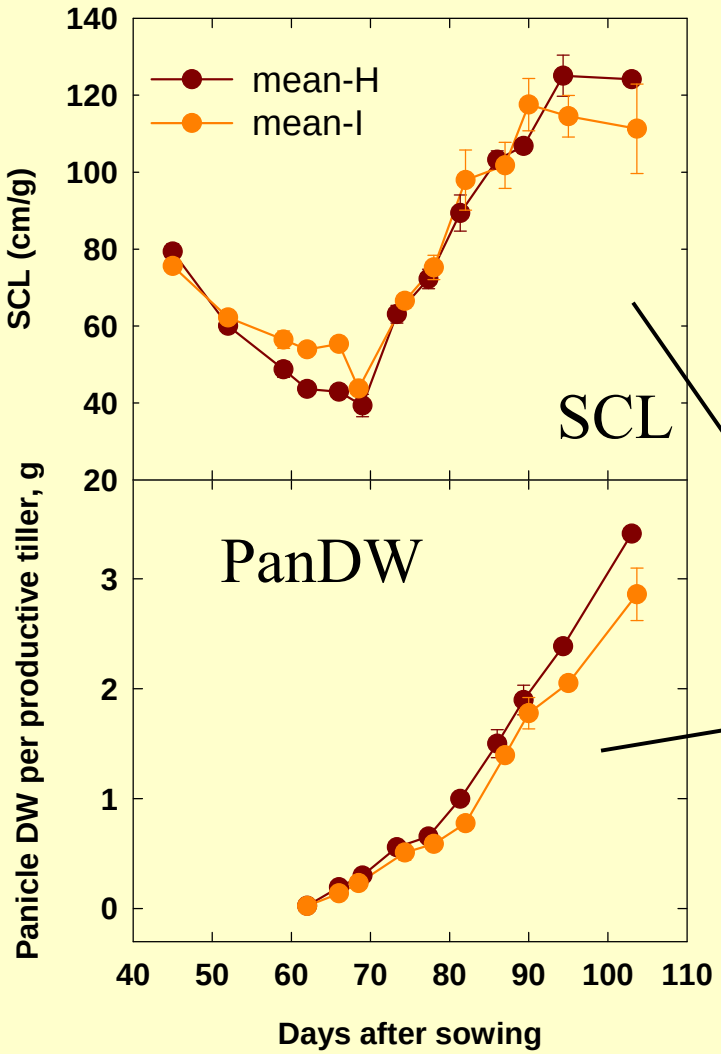
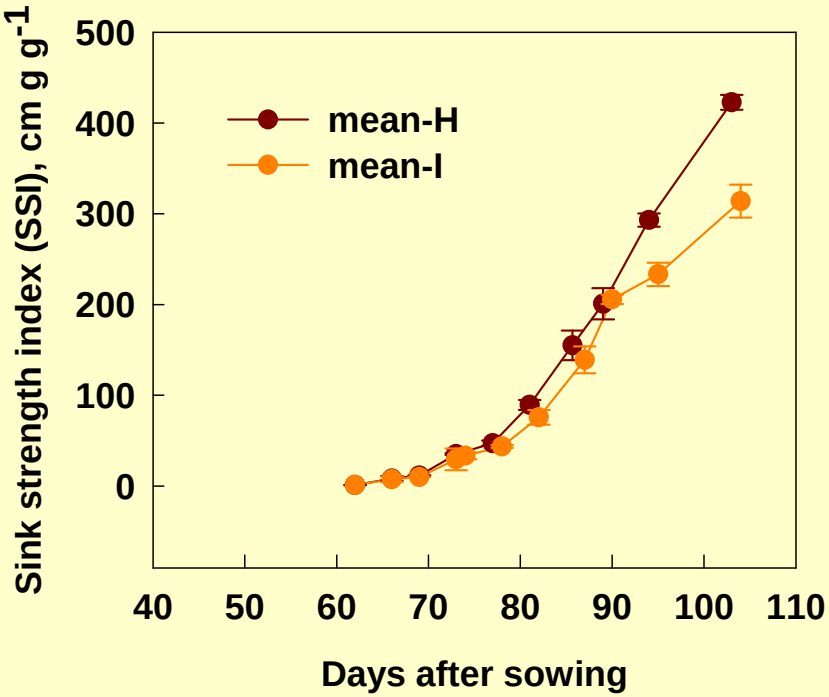
Higher harvest index: designing an improved index



Designing an index that accounts for the efficiency of the partitioning better than the harvest index: that integrates stem vigor (reverse of SCL) together with panicle dry weight without consideration of leaf and sheath dry matter: sink strength index

SSI = PaDW x SCL



Hybrid: a weaker stem bears a heavier panicle however, higher sensitivity to lodging

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Higher harvest index: designing an improved index

Using the sink strength index (SSI) to compare the efficiency of partitioning between hybrids and inbreds in a large set of situations

Year/ Season		GY (t/ha)	ShDW m^{-2}	HI	SSI (g cm g^{-1})
2007 DS	H (7)	11.03 a	2108 a	0.54 a	175 a
Transplanting	I (6)	9.48 b	1932 b	0.50 b	145 b
2006 DS	H (3)	8.45 a	1780 a	0.51 a	150 a
Staggered	I (3)	7.53 b	1634 a	0.45 b	102 b
2006 DS	H (2)	8.49 a	1587 a	0.55 a	156 a
AWD genotypes	I (3)	8.44 a	1611 a	0.52 b	133 b
2005 DS	H (2)	7.16 a	1959 a	0.45 a	114 a
Braodcasting	I (2)	5.94 b	1820 a	0.42 a	93 b
2004 WS	H (5)	5.93 a	1885 a	0.45 a	140 a
Wet season	I (7)	5.35 b	1748 b	0.42 b	117b

The difference in SSI between plant types is larger than that in HI, and with stronger significance

SSI at maturity can be used more acurately than harvest index to discriminate plants in their ability to partition dry matter efficiently

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General conclusion

- **No detrimental effect of the number of non-productive tillers on grain yield and harvest index as long as high-yielding genotypes are concerned**

- **Higher biomass accumulation in hybrid rice:**
  - does leaf angle play a role and during the whole crop cycle?
  - do leaf senescence and remobilization from leaf play a role during grain filling?

- **More efficient sink regulation (to be associated to sugar metabolism, data to come soon) is essential to increase high yield potential:**
  - Early and quick tiller emergence, already with most high-yielding inbreds and hybrids
  - quicker increase in allocation to the culm before PI
  - quicker increase in allocation to the panicle during culm growth
  - more biomass remobilized from the culm
  - more spikelets filled at a time during the whole filling period
  - lighter unfilled grains

  } more efficient in hybrid rice

- **Higher early hybrid vigor:**
  - the individual seed size and SLA do not play a role
  - Is it due to more efficient sink regulation?

- **High susceptibility to lodging in high-yielding hybrid rice:**
  - some hybrids show some resistance (Islam et al 2007): lower SCL of lower internodes.

  What about their sink regulation and yield potential? Considering environmental risk for lodging?

- **Crop management:**
  - hybrids and inbreds respond similarly to seedling age at transplanting and to direct-seeding
  - nitrogen management has been identified as a practice to adapt to plant type (Peng et al) with spikelet number increasing linearly with increase in N concentration (Horie et al 2003)

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Breeding strategy for yield potential and proposed usable traits

for which variability already exists amongst high-yielding genotypes

The potential sink size of the high-yielding genotypes is already high and varies across genotypes and environments (Sheehy et al 2001 + moderate spikelet filling percentage)

It appears that the plant adapt its actual sink size to its potentialities (sink regulation) and to the environment (source strength)

The breeding strategies for yield potential should go for higher sink regulation and higher source strength (importance of CGR two weeks before heading which is also the time for spikelet degeneration and husk size determination, Horie et al 2003), not for higher sink size. However, selecting for higher sink size may account for higher sink regulation

Usable traits for increasing sink regulation:

- **During the vegetative stage:**
  - Low maximum tiller number at PI (tiller count) associated with early and quick tiller emergence
- **At flowering:**
  - Low sink strength index (stem length, stem dry weight, panicle dry weight): high reserve storage
- **At maturity:**
  - High sink strength index (stem length, stem dry weight, panicle dry weight)
  - Low individual unfilled grain size (1000 unfilled grain dry weight)

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Possible candidates traits for increasing yield potential

for which no variability or no scientific evidence has been identified amongst high-yielding genotypes

- **Increasing the source:**
  - Decreased leaf angle (more erect leaf)?
  - Increased clump plasticity at early stage?
  - Extended culm growth period vs. vegetative (Slafer et al)?
  - Extended grain filling period?
  - Delayed root senescence in order to delay leaf senescence?
  - C4 rice (Sheehy et al)?
- **Increasing sink regulation**
  - Increased specific leaf area at early stage?
  - Increased dry matter remobilization from culm and senescing tillers?
- **Reducing respiratory cost during culm growth and grain filling**

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