Interaction of environmental factors affecting wheat performance
- A case for multidisciplinary research efforts

**Topic:**
There has been recent progress in individual scientific disciplines, but these advances within single disciplines, alone, cannot solve the challenges of increasing yield.

Therefore multidisciplinary approaches must be implemented to tackle major constraints to achieving sufficient grain yield in the future.
Grain production and consumption

World Grain Production and Consumption, 1960-2011

- Dangerously small margin between grain consumption and grain production
- We face long-term trends that:
  - increase food demand
  - limit food production
Environmental and agronomical constraints to crop yield and quality

Agronomical factors and environmental constraints will influence the levels of a wide range of (in)organic compounds in crops that in turn affect key physiological processes and may finally affect grain yield and quality.

Environmental and agronomical constraints to crop yield and quality

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Consequence:
The need to focus on $G \times E \times M$

Constraints to crop yield and quality

Stagnation of yield in winter wheat

[Graph showing yield trends in countries like Norway, Finland, UK, Germany, Denmark, Spain, Greece, and Italy from 1960 to 2008. The x-axis represents the year, and the y-axis represents yield (Mg ha\(^{-1}\)) and grain yield (Mg ha\(^{-1}\)).]
Constraints to crop yield and quality

Indicators of a Warming World

- Glaciers
- Temperature Over Land
- Snow Cover
- Permafrost retreating poleward
- Tree-lines shifting poleward and upward
- Spring coming earlier
- Species migrating poleward and upward
- Humidity
- Temperature Over Oceans
- Air Temperature Near Surface (troposphere)
- Sea Surface Temperature
- Ice Sheets
- Sea Level
- Sea Ice
- Ocean Heat Content
Climate change will increase the **frequency, intensity and duration** of periods with extreme climatic conditions.
Climate change: What are the risks?

2001

Level of additional risk due to climate change
- Undetectable
- Moderate
- High
- Very high
Climate change: What are the risks?

Risks from climate change, by reason for concern [Smith et al. PNAS 2009]
Climate change: What are the risks?

IPCC WGII AR5
Summary for Policymakers
(2014)
Climate change: Paradigm shift

Earlier research concluded that the initial stages of climate change would bring net benefits to global agriculture due to carbon fertilization and longer growing seasons.

Newer experimental studies have sharply reduced older estimates of carbon fertilization effects.

The effect of temperature on many crops has been found to involve thresholds, above which yields rapidly decline.
**Temperature thresholds**

<table>
<thead>
<tr>
<th>Processes</th>
<th>Mean temperature (± se) (°C)</th>
<th>n</th>
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<td>35.4 (2.0)</td>
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</table>

$n$ is the number of literature sources used to calculate means and se.
Drought and heat waves reduce crop yield

Crop yields can drop by 3 – 5% with every 1°C increase in temperature

Temperature change forecast 2071-2100 period, relative to the 1961-1990 period

..Global maize and wheat production declined by 3.8% and 5.5%, respectively...

Climate trends were large enough in some countries to offset a significant portion of the increases in average yields that arose from technology, CO₂ fertilization, and other factors...

Climate Trends and Global Crop Production Since 1980
David B. Lobell, Wolfram Schlenker, Justin Costa-Roberts
Scienceexpress 5 May 2011
How to live with climate change

Stopping climate change

How to feed the world

A 14-PAGE SPECIAL REPORT

Dealing with America's deficit
Obama's timid trip to Asia
Remote control for your car
Peter Drucker, still king of the gurus
The scientist who saw Nessie
The response to environmental stress is complex.
• Biotic stress vs. abiotic stress
• Abiotic Stress Interactions:
  single vs. multiple stress events
  single vs. multiple stress types

Little is known about the interaction of these stresses and the consequences for crop quality
Interaction of high-temperature events

Climate Change, Climatic Variability and Agriculture in Europe: An integrated Assessment (CLIVARA)

Double-ridge stage (the spikelet formation phase, in which two bracts mark the end of the spikelet)

Outdoor temperatures at the experimental site

Anthesis

Final harvest
Interaction between stress events & stress types

Water deficits:
Exploring the asynchronous protein metabolism in single kernels of wheat studied by NMR spectroscopy and chemometrics.
Winning, H.; Viereck, N.; Wollenweber, B.; Larsen, F.H.; Jacobsen, S.; Søndergaard, I.; Balling Engelsen, S.

Global dimming:
Long-term low radiation decreases leaf photosynthesis, photochemical efficiency and grain yield in winter wheat.
Mu, H.; Jiang, D.; Wollenweber, B.; Dai, T.; Jing, Q.; Cao, W.

Effects of shading on morphology, physiology and grain yield of winter wheat.
Li, H; Jiang, D.; Wollenweber, B.; Dai, T.; Cao, W.

Waterlogging + water deficits:
Effects of post-anthesis drought and waterlogging on accumulation of high molecular-weight glutenin subunits and glutenin macro polymer content in wheat grain.
Jiang, D, Yue, H., Wollenweber, B., Tan, W., Dai, T., Jing, Q., Cao, W.

Waterlogging pretreatment during vegetative growth improve tolerance to waterlogging after anthesis in wheat.
Li, C; Jiang, D.; Wollenweber, B.; Li, Y.; Dai, T.; Cao, W.
*Plant Science* 180: 672-678 (2011)

High-temperature + water deficits:
Implications of high-temperature events and water deficits on protein profiles in wheat (Triticum aestivum L. cv. Vinjett) grain.
Yang, F., Dysted Jørgensen, A., Li, H., Søndergaard, I., Finnie, C., Jiang, D., Wollenweber, B., Jacobsen, S.
*Proteomics* 11: 1684-1695 (2011)
Interaction between stress events & stress types

Temperature-extremes are more important than CO$_2$-increases for crop yields

Critical temperature thresholds need identification

The study of adaptation to extreme weather conditions requires a more integrated research approach

The need for an integrated research approach

Despite recent achievements in conventional plant breeding and genomics, the rate of increase of crop yields is declining.

Advances within single disciplines, alone, cannot solve the challenges of increasing yield.

There has been recent progress in individual disciplines, but multidisciplinary approaches must be implemented to tackle major constraints to achieving sufficient grain yield in the future.
The need for an integrated research approach

**Advances in Genetics**
- enhanced marker technology
- enhanced QTL detection methods
- enhanced genotype to phenotype linkages

**Advances in Physiology**
- the plants perspective (sensing stress)
- complex trait physiology
- prediction of consequences of genetic variation

**Advances in Modelling**
- Climate, agronomical, physiological & biochemical models

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The need to understand the effects of gene function on crop performance under various environmental conditions and the processing of this knowledge into robust simulation models

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The need for an integrated research approach

FAO Director-General appeals for second Green Revolution

Vast effort needed to feed billions and safeguard environment

13 September 2006, Rome/San Francisco – FAO Director-General Jacques Diouf today called for a second Green Revolution to feed the world’s growing population while preserving natural resources and the environment.

Addressing a meeting of the World Affairs Council of Northern California in San Francisco, Dr Diouf said:

“in the next few decades, a major international effort is needed to feed the world when the population soars from six to nine billion. We might call it a second Green Revolution.”

The San Francisco-based World Affairs Council of Northern California, which has 10,000 members, is one of the United States’ leading non-governmental fora for discussion and debate of international affairs.

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(+39) 06 570 53762

Genetics
Modelling
Physiology
Agronomy
Implementation – The ‘Heat-Wheat’ project

Strategic research objectives

to exploit synergies between agronomic, physiological and genetic research and crop modeling

to screen for key regulatory processes of adaptation to high-temperature episodes

Key traits
Photosynthesis
Stress response
Grain yield and quality
‘Heat-Wheat’ project - Framework

Physiology - development of phenotyping tools
  Screening for heat stress tolerance

Genetics - QTL’s
  Introduction of genes by marker assisted backcrossing
  Detailed mapping of major genes for stress tolerance

Agronomy - Impact assessment
  Genotypic stress responses on phenology, yield and quality

Modelling - Impact prediction
  Modeling genotype responses to heat stress
Phenotyping leaves

$F_v/F_m$ (maximum quantum efficiency of PS$_{II}$) in leaves can be used as a phenotyping tool to screen for heat tolerance.

1274 cultivars scanned → 138 → 41 cultivars selected

Lowest Performance Highest

Control

Heat

Genetics
Modelling
Physiology
Agronomy

Phenotyping of wheat cultivars for heat tolerance using chlorophyll a fluorescence
Heat stress effects on phenology and yield

‘Semi-field’ experiments with 140 -> 15 cultivars

Single seed near infrared (NIR) transmission spectroscopy

ECVA score plot of two first components of selected samples for control and heat treatments

Generation of mapping population

Genotyping -> Linkage analysis -> QTL mapping

- 3 heat inducible QTLs related to $F_v/F_m$ mapped

Heat stress effects on phenology

Heat stress impact

‘Semi-field’ experiments 15 cultivars
Field experiment with 9 cultivars

>> Reduction in grain filling duration

<table>
<thead>
<tr>
<th>Cultivar number</th>
<th>Cultivar name</th>
<th>Source</th>
<th>Geographical origin</th>
<th>Height (cm)</th>
<th>GS31</th>
<th>GS65</th>
<th>GS92 Control</th>
<th>Heat (ADays)</th>
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<td>53</td>
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<td>IPK</td>
<td>Denmark</td>
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<td>97</td>
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<td>84</td>
<td>133</td>
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</table>

GS31: the start of stem elongation; GS65 is the mid-flowering stage; GS92 is maturity (BBCH scale); expressed as days after sowing (DAS).

Traits in spring wheat cultivars associated with yield loss caused by a heat stress episode after anthesis.
Heat-stress effects on yield

Genotype response -yield traits

Average grain weight (GW, mg dry matter), grain dry matter yield (GY, mg plant⁻¹), grain N yield (GNY, mg plant⁻¹), stem water soluble carbohydrates (SWSC, mg plant⁻¹) and harvest index (HI) at maturity.

| GW  | GY   | GNY  | SWSC | HI   | GW  | GY   | GNY  | SWSC | HI   |
|-----|------|------|------|------|-----|------|------|------|------|------|
| 810 | 47   | 1224 | 247  | 61   | 0.52| -4   | 171  | -73  | -2   | -0.05|
| 490 | 38   | 1044 | 287  | 67   | 0.48| -1   | 116  | -70  | 296  | -0.12|
| 1039| 52   | 1339 | 207  | 55   | 0.49| -13  | 336  | -12  | -12  | -0.06|
| 1110| 36   | 1317 | 225  | 120  | 0.48| -4   | 164  | -30  | -16  | -0.13|
| Taifun| 46  | 1489 | 291  | 63   | 0.61| -12  | 195  | -56  | -30  | -0.02|
| Tercie| 39  | 1958 | 276  | 35   | 0.65| -9   | 291  | -60  | 1    | -0.07|
| Vinjett| 44  | 1677 | 320  | 42   | 0.54| -16  | 541  | -93  | 0    | -0.14|
| 1216| 41   | 1499 | 240  | 101  | 0.53| -13  | 491  | -47  | -50  | -0.10|
| 1159| 39   | 1667 | 147  | 16   | 0.59| -5   | 138  | 43   | 5    | 0.01 |
| 1194| 43   | 1571 | 300  | 224  | 0.35| -18  | 560  | -130 | 79   | -0.03|
| 882 | 33   | 1580 | 231  | 387  | 0.44| -12  | 498  | -47  | -336 | -0.09|
| 579 | 37   | 1209 | 201  | 281  | 0.41| -6   | 217  | -21  | -183 | -0.05|
| 844 | 44   | 1320 | 186  | 1607 | 0.36| 7    | 118  | 32   | 1033 | -0.02|
| 633 | 49   | 1202 | 188  | 1292 | 0.32| -15  | 248  | -21  | -851 | -0.02|
| 830 | 50   | 1097 | 138  | 1536 | 0.36| -15  | 558  | -28  | -240 | -0.15|

Also highest reduction in grain filling duration.
Heat-stress effects on photosynthesis

Effects of heat stress on net photosynthetic CO$_2$ assimilation rate (Pn), stomatal conductance (gs), transpiration rate (Tr), and chlorophyll content (SPAD) in leaves

<table>
<thead>
<tr>
<th>Varieties</th>
<th>Pn Control</th>
<th>Heat</th>
<th>gs Control</th>
<th>Heat</th>
<th>Tr Control</th>
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<td>15.6ab</td>
<td>0.20b</td>
<td>0.35b</td>
<td>1.2d</td>
<td>5.9cde</td>
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<td>11.4cd</td>
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<td>13.9bc</td>
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<td>1.8cd</td>
<td>5.2def</td>
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<td>42.0d</td>
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</table>

Varieties *** Treatments ns Varieties × Treatments ***

Pn (μmol CO$_2$ m$^{-2}$ s$^{-1}$); gs (mol H$_2$O m$^{-2}$ s$^{-1}$); Tr (mmol H$_2$O m$^{-2}$ s$^{-1}$); Chl content (SPAD: Soil Plant Analysis Development meter value). Data are means of the three biological replicates (n=3). Different lowercase letters denote statistically significant differences (P<0.05) among varieties as analysed by Duncan's Multiple Range Test. Different superscript uppercase letters indicate statistically significant differences (P<0.05) between control and heat treatment within the same variety. ***: significant difference at P<0.01. **: significant difference at P<0.05. ns: no significant difference. Decrease Increase

Heat-stress effects on leaf proteins

2-DE gels of wheat leaf proteins in variety 810 (A) and 1039 (B)

Rubisco activase
Rubisco small subunit
Rubisco large subunit

up-regulated in 810 (Tolerant)
down-regulated in 1039 (Susceptible)

Other identified proteins:
Heat shock proteins
Stress defense

Multiple stress events and multiple stress types

Treatments

c: control; wd: water deficits; ht: high temperature

Treatments were applied at end of spikelet initiation (A) and/or anthesis (B)

Changes in grain nr

Conclusions

Heat had a larger impact than drought
Larger impact when applied at anthesis
Drought - no significant differences

Implications of high-temperature events and water deficits on protein profiles in wheat (Triticum aestivum L. cv. Vinjett) grain
Multiple stress events and multiple stress types

Conclusions

Changes in grain protein contents strongly depended on the type of stress interactions applied

Identified proteins responsive to stress episodes play roles in: anti-desiccation, anti-oxidation, carbohydrate metabolism

Implications of high-temperature events and water deficits on protein profiles in wheat (Triticum aestivum L. cv. Vinjett) grain
Beneficial interaction of multiple stress events?

Pre-exposure to mild drought stress during vegetative growth

NN: Non-primed
NP: Priming at stem-elongation
PP: Priming at tillering and stem-elongation
Beneficial interaction of multiple stress events?

Pre-exposure to mild stress during vegetative growth → effects on stress after anthesis

NN: Non-primed
NP: Priming at stem-elongation
PP: Priming at tillering and stem-elongation

NNC: Control
NND: NN+DS (drought stress)
NPD: NP+DS
PPD: PP+DS
Primed plants improved photosynthesis and ROS scavenging efficiency under drought stress.

Effects of drought priming on photosynthesis rate ($A_{net}$) and Ascorbate peroxidase (APX) activity in wheat leaves under drought stress.

**Priming**

Differently expressed leaf proteins in primed plants

<< after priming >>

<< after drought stress >>
Priming

Primed plants modified protein expression

- Rubisco activase
- Rubisco small subunit
- Ascorbate peroxidase
- Cytosol fructose bisphosphate aldolase
- Plastid glutamine synthetase isoform GS2c
- Oxygen-evolving enhancer protein 1

Improved tolerance to drought stress after anthesis due to priming before anthesis in wheat (Triticum aestivum L.) var. Vinjett
‘Heat-Wheat’ project - Conclusions

Physiology - Phenotyping tools established
- Screening for heat stress with $F_v/F_m$
- Single seed near infrared (NIR) transmission spectroscopy

Genetics - QTL’s
- 3 heat inducible QTLs related to $F_v/F_m$ mapped

Agronomy - Impact assessment
- Genotype responses to heat and drought stress & combinations
- Priming might have the potential to contribute to enhanced tolerance

Modeling - Impact prediction
- Modeling genotype response to changes in temperature
To tackle the challenges facing society (energy, water, climate, food, health), **scientists and social scientists must work together.**

Yet research that transcends traditional academic boundaries is still unfashionable and poorly rewarded.
## Acknowledgements

<table>
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Thank you!