Genetics-based breeding in winter wheat has lead to modern elite varieties with broad resistance to major diseases – A success story

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Development of annual average grain yield (dt/ha) in major wheat producing countries of Europe

Wheat yield in Europe in the last 5 decades

Annual rate in D: 103 kg/ha/a
(AgriStat. 1966-2007)

P = G + T + U + GT + GU + GTU
### Major fungal diseases and causal pathogens of wheat

<table>
<thead>
<tr>
<th>Disease</th>
<th>Pathogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAUSED BY BIOTROPHIC FUNGI</td>
<td></td>
</tr>
<tr>
<td>Powdery Mildew</td>
<td><em>Blumeria graminis</em></td>
</tr>
<tr>
<td>Leaf (Brown) Rust</td>
<td><em>Puccinia triticina</em></td>
</tr>
<tr>
<td>Stripe (Yellow) Rust</td>
<td><em>Puccinia striiformis</em></td>
</tr>
<tr>
<td>Stem (Black) Rust</td>
<td><em>Puccinia graminis</em></td>
</tr>
<tr>
<td>Septoria tritici blotch (STB)</td>
<td><em>Septoria tritici</em></td>
</tr>
<tr>
<td>CAUSED BY NECROTROPHIC FUNGI</td>
<td></td>
</tr>
<tr>
<td>Fusarium Head Blight (FHB)</td>
<td><em>Fusarium ssp.</em></td>
</tr>
</tbody>
</table>
Field experiments, 6 locations (BRIWECS project)
Aim: Understanding innovation decisions for cereal breeding

Phenotyping
Estimating fungal diseases by % organ area infected (1 to 4x)
Phenological growth stages
Yield and yield components (cutting sample and combine harvester)

Helios
JKI Quedlinburg

Desamo
Treatment T1, 26/05/2015 (BBCH 37)
Field phenotyping of reaction to major diseases
JKI Quedlinburg, 2 years (2015 & 2016)

Stripe and leaf rust inoculation

220 varieties
4 treats, 2 reps = 1,760 plots
Incomplete block design

Fusarium inoculation

www.briwecs.de
Breeding innovation – resistance by year of release

Stripe rust

- 110 kg N/ha: -0.15%/a, $r = -0.36$ ***
- 220 kg N/ha: -0.19%/a, $r = -0.39$ ***

Powdery mildew

- 110 kg N/ha: -0.12%/a, $r = -0.60$ ***
- 220 kg N/ha: -0.13%/a, $r = -0.60$ ***

Years 2015 & 2016

$\%$ leaf area diseased

$\%$ leaf area diseased

Holger Zetzsche, JKI

$r$ correlation coefficient

*** significant with $p<0.001$
### Sources of resistance of wheat against powdery mildew

<table>
<thead>
<tr>
<th>Resistance Code</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pm1</strong></td>
<td><em>Triticum aestivum, Normandie</em></td>
</tr>
<tr>
<td><strong>Pm2</strong></td>
<td><em>Triticum aestivum, Ulka</em></td>
</tr>
<tr>
<td><strong>Pm3a</strong></td>
<td><em>Triticum aestivum, Asosan</em></td>
</tr>
<tr>
<td><strong>Pm3b</strong></td>
<td><em>Triticum aestivum, Chul</em></td>
</tr>
<tr>
<td><strong>Pm3c</strong></td>
<td><em>Triticum aestivum, Sonora</em></td>
</tr>
<tr>
<td><strong>Pm3d (syn. Mlk)</strong></td>
<td><em>Triticum aestivum, Kolibri</em></td>
</tr>
<tr>
<td><strong>Pm4a</strong></td>
<td><em>Triticum dicoccum, Khapli</em></td>
</tr>
<tr>
<td><strong>Pm4b</strong></td>
<td><em>Triticum carthlicum, Armada</em></td>
</tr>
<tr>
<td><strong>Pm5</strong></td>
<td><em>Triticum dicoccum, Hope</em></td>
</tr>
<tr>
<td><strong>Pm6</strong></td>
<td><em>Triticum timopheevi, TP 114</em></td>
</tr>
<tr>
<td><strong>Pm8</strong></td>
<td><em>Secale cereale, Disponent</em></td>
</tr>
<tr>
<td><strong>Pm9</strong></td>
<td><em>Triticum aestivum, Normandie</em></td>
</tr>
<tr>
<td><strong>Pm17</strong></td>
<td><em>Secale cereale, Amigo</em></td>
</tr>
<tr>
<td><strong>Pm46</strong></td>
<td><em>Triticum aestivum, Tabasco</em> (5DS)*</td>
</tr>
<tr>
<td><strong>Mld</strong></td>
<td><em>Triticum durum, Maris Dove</em></td>
</tr>
<tr>
<td><strong>MlAx</strong></td>
<td><em>Triticum aestivum, Axona</em></td>
</tr>
<tr>
<td><strong>MlCo3</strong></td>
<td><em>Triticum aestivum, Cornett (=Kadett)</em></td>
</tr>
<tr>
<td><strong>MIHa2</strong></td>
<td><em>Triticum aestivum, Haven</em></td>
</tr>
<tr>
<td><strong>MITa2</strong></td>
<td><em>Triticum aestivum, Talent</em></td>
</tr>
<tr>
<td><strong>U</strong></td>
<td>unbekannt, unterschiedlicher Herkunft</td>
</tr>
</tbody>
</table>

46 identified powdery mildew resistance genes (loci)

Red = present in current resistant cultivars (rating 1)

[German Descript. Variety List 2016]

Pm3 together with its multiple alleles, Pm38, Pm8 and a key member of Pm21 have been cloned.
## Mildew Resistant Winter Wheat Cultivars, Germany 2016 (Rating 1)

<table>
<thead>
<tr>
<th>Wheat variety</th>
<th>Source</th>
<th>Breeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apostel *</td>
<td>U</td>
<td>4046</td>
</tr>
<tr>
<td>Bosporus *</td>
<td>U</td>
<td>8887</td>
</tr>
<tr>
<td>Dekan</td>
<td>Pm4b, Pm5, Pm6</td>
<td>129</td>
</tr>
<tr>
<td>Design *</td>
<td>U (Pm17?)</td>
<td>1410</td>
</tr>
<tr>
<td>Edward</td>
<td>Pm46</td>
<td>25</td>
</tr>
<tr>
<td>Gustav</td>
<td>U</td>
<td>25</td>
</tr>
<tr>
<td>Halvar</td>
<td>Pm2, Pm4b, Pm6</td>
<td>6918</td>
</tr>
<tr>
<td>Hyland +</td>
<td>U</td>
<td>9056</td>
</tr>
<tr>
<td>Moschus *</td>
<td>Pm3a, Pm5</td>
<td>214</td>
</tr>
<tr>
<td>Nordcap *</td>
<td>Pm2, Pm3a</td>
<td>9056</td>
</tr>
<tr>
<td>Sheriff *</td>
<td>U</td>
<td>9925</td>
</tr>
<tr>
<td>Tabasco</td>
<td>Pm46</td>
<td>25</td>
</tr>
</tbody>
</table>

+ = hybrid cultivar, *) new registration, U = unknown (*Triticum dicoccoides*?)

25= BE, 129= KWS, 214= STR, 1410= SEC, 4046= Streng, 6918= Sejet, 8887= Breun, 9056= NORD, 9925= Intersz

*Pm3 with its multiple alleles, Pm38, Pm8 and a key member of Pm21 have been cloned*
New QTL on 6A, 2A, 3D?

GWAS - Manhattan-Plot: Stripe rust (2015, 2016)

JMP Genomics 8 (SAS 9.4): Q-K Mixed model, P <0.001

Ref. WANG map

Holger Zetzsche, JKI

Jagger_c1423_102

R²exp 5.7%
GWAS - Manhattan-Plot: Powdery mildew (2015, 2016)

JMP Genomics 8 (SAS 9.4): Q-K Mixed model, P <0.001

Known QTL on 2A, 2B and 7A, 7B

QTL on 5BL close to Pm36?

R²exp 5.1%

Kukri_c62247_248

% leaf area diseased

Holger Zetzche, JKI
Breeding innovation – resistance by year of release

**Fusarium head blight (FHB)**

- 110 kg N/ha -0.02%/a  \( r = -0.27 \) ***
- 220 kg N/ha -0.03%/a  \( r = -0.26 \) ***

**Septoria tritici blotch (STB)**

- 110 kg N/ha + 0.01%/a  \( r = 0.14 \) *
- 220 kg N/ha +0.01%/a  \( r = 0.14 \) *

% ear area diseased  

% leaf area diseased  

Year of release  

Year of release  

\( r \) correlation coefficient  

***, * significant with p<0.001, <0.05  

Holger Zetzsche, JKI
GWAS - Manhattan-Plot – FHB (years 2015, 2016)

JMP Genomics 8 (SAS 9.4): Q-K Mixed model, P <0.001

- FHB resistance QTL:
  - Known on 7BL
  - New QTL on 3A?

Holger Zetzsche, JKI
Impact of fungal diseases on grain yield

Yield = 8.8 - 0.13 x Fungal dis. sum %  \( r = -0.77 \) ***

1% fungal disease* ~ 130 kg/ha grain yield

*) Powdery mildew + Leaf rust + Stripe rust + FHB + STB

\( r \) correlation coefficient
*** significant at \( p<0.001 \)

Holger Zetzsche, JKI
Yield stability of varieties released since the 1960s

193 varieties, 10 environments (2 years: 2015, 2016, 5 locations in Germany)

T1 = 110 kgN/ha, no fungicide (N1, PP-)
T2 = 220 kgN/ha, no fungicide (N2, PP-)
T3 = 220 kgN/ha, with fungicide (N2, PP+)

Yield stability of varieties released since the 1960s

193 varieties, 10 environments (2 years: 2015, 2016, 5 locations in Germany)

T1 = 110 kgN/ha, no fungicide (N1, PP-)
T2 = 220 kgN/ha, no fungicide (N2, PP-)
T3 = 220 kgN/ha, with fungicide (N2, PP+)

Benny Wittkop, UGi
Fungicide effect on yield stability of varieties released since the 1960s
193 varieties, 10 environments (2 years: 2015, 2016, 5 locations in Germany)

Trend: Modern varieties are more stable than older ones!
Yield stability of varieties released since the 1960s

193 varieties, 10 environments (2 years: 2015, 2016, 5 locations in Germany)

Increased yield level + stability (ecovalence)

\[
\text{Ecoval} \left( s_i \right) = \sum_{j=1}^{b} (s_{ij})^2; s_{ij} = y_{ij} - y_i - y_j + y_s
\]

\[
\text{s\% (EV cv)} = \sqrt{\text{Ecoval} \left( s_i \right) / b} \times 100 / y_i
\]

\( i \) = variety; \( j \) = treatment

\( R^2 = 0.0856 \)
Consequences for resistance breeding

1. Great improvement of wheat by **phenotypic selection**: powdery mildew > rusts > FHB

2. **Pyramiding** (combination) of functional loci by MAS

3. **Isolation and characterization** of resistance genes (e.g. mildew, rusts), allowing transfer and direct selection

4. Direct mutations in isolated genes by **gene editing** (e.g. CRISPR-Cas)

5. **Genomic selection** for oligo- or polygenic (quantitative) and potentially durable resistance

6. **Future**: Resistance/tolerance to abiotic stresses!
Thanks

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