

Genomic prediction models for grain yield of spring bread wheat in diverse agro-ecological zones

C. Saint Pierre^{1¶}, J. Burgueño^{1¶}, J. Crossa^{1¶}, G. Fuentes Dávila², P. Figueroa López², E. Solís Moya², J. Ireta Moreno², V. M. Hernández Muela², V. Zamora Villa³, P. Vikram¹, K. Mathews¹, C. Sansaloni¹, D. Sehgal¹, D. Jarquin⁴, P. Wenzl^{1§} and Sukhwinder-Singh^{1*}

¹International Maize and Wheat Improvement Center (CIMMYT), Km. 45, Carretera México-Veracruz, El Batán, Texcoco, México, CP 56237

²Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, INIFAP, México;

³Universidad Autónoma Agraria Antonio Narro, México;

⁴Department of Agronomy and Horticulture, University of Nebraska-Lincoln, 321 Keim Hall, Lincoln, NE, 68503-0915, USA

[§]Present address: Centro Internacional de Agricultura Tropical (CIAT), Km 17 Recta Cali-Palmira, 763537 Cali, Colombia

[¶] First three authors contributed equally to this work.

* Corresponding author:

Sukhwinder-Singh, Wheat Lead, Seeds of Discovery (SeeD) initiative

International Maize and Wheat Improvement Center (CIMMYT)

Km. 45, Carretera México-Veracruz, El Batán, Texcoco CP 56130

Edo. de México. MEXICO

E-mail: suk.singh@cgiar.org

Mexico City: +52 (55) 5804 2004

Texcoco, México: +52 (595) 952 1900; ext. 2104, Mobile: +52 1 595 1255378

Supplementary Table 1: List of sites (city and State in Mexico), coordinates (latitude, longitude and altitude), wheat cycle (sowing and harvesting date), and meteorological data including average, maximum and minimum temperature, for the environments where the wheat panel was sown.

| Site | Coordinates | Wheat Cycle | Month | Temp average | Temp max | Temp Min |
|------------------------------|--|-----------------------------------|--------|--------------|----------|----------|
| Celaya, Guanajuato | 20 34 48 N 100 49 11 W 1,752 metres above sea level (masl) | Winter 29-Nov2011- May2012 | Nov-11 | 17.53 | 25.14 | 10.29 |
| | | | Dec-11 | 16.76 | 24.94 | 9.12 |
| | | | Jan-12 | 15.84 | 23.17 | 8.91 |
| | | | Feb-12 | 16.69 | 22.93 | 11.29 |
| | | | Mar-12 | 20.19 | 27.73 | 12.59 |
| | | | Apr-12 | 21.84 | 29.38 | 14.05 |
| Delicias, Chihuahua | 28 23 51 N 105 30 44 W 1,166 masl | Winter 13-Jan2012- Jun2012 | Jan-12 | 12.86 | 23.16 | 2.56 |
| | | | Feb-12 | 13.24 | 22.18 | 4.29 |
| | | | Mar-12 | 17.03 | 27.16 | 6.90 |
| | | | Apr-12 | 23.17 | 32.93 | 13.40 |
| | | | May-12 | 25.88 | 34.73 | 17.03 |
| | | | Jun-12 | 29.38 | 37.93 | 20.83 |
| Tepatitlán, Jalisco | 20 31 422 N 102 51 62 W 1,930 masl | Winter 4-Jan2012- Junio2012 | Jan-12 | 17.03 | 27.53 | 6.53 |
| | | | Feb-12 | 17.91 | 26.41 | 9.41 |
| | | | Mar-12 | 21.10 | 31.61 | 10.58 |
| | | | Apr-12 | 22.01 | 33.15 | 10.87 |
| | | | May-12 | 24.89 | 35.68 | 14.10 |
| | | | Jun-12 | 24.78 | 34.42 | 15.13 |
| Ciudad Obregón, Sonora | 27 22 12 N 109 55 43 W 39 masl | Winter 1-Dec2011- Apr2012 | Dec-11 | 15.50 | 24.40 | 6.60 |
| | | | Jan-12 | 15.48 | 28.54 | 6.26 |
| | | | Feb-12 | 16.70 | 25.70 | 7.70 |
| | | | Mar-12 | 18.15 | 28.30 | 8.00 |
| | | | Apr-12 | 21.40 | 31.70 | 11.10 |
| Zaragoza, Coahuila | 28 35 56 N 100 54 43 W 343 masl | Winter 7-Dec2011- May2012 | Dec-11 | NA | NA | NA |
| | | | Jan-12 | NA | NA | NA |
| | | | Feb-12 | 16.02 | 23.9 | 10.39 |
| | | | Mar-12 | 19.51 | 27.41 | 12.23 |
| | | | Apr-12 | 23.5 | 31.15 | 15.42 |
| | | | May-12 | 23.54 | 30.22 | 18.44 |

Source: CIMMYT, INIFAP, <http://clicom-mex.cicese.mx>

Supplementary Table 2: Average correlation (and standard deviation in parenthesis) between observed and predicted values for two random cross-validation schemes for traits days to anthesis and maturity, and plant height in five sites in Mexico; L=line, E=site, G=genotypic information, A=pedigree, W=environmental variables and interactions. Cross-Validation CV1: predictions when a proportion of lines are not included in any of the 5 sites; Cross-Validation CV2: predictions when a proportion of lines is removed from some of the sites though leave in others.

| Sites | | Genomic Model | | | | | | |
|------------------------------|------------|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | L+E+W | E+W+G | E+W+G+GE | E+W+A | E+W+A+AE | E+W+G+A | E+W+G+A+GE+AE |
| ----- Days to anthesis ----- | | | | | | | | |
| CV1 | Celaya | -0.026 (0.048) | 0.577 (0.013) | 0.588 (0.013) | 0.540 (0.011) | 0.552 (0.012) | 0.622 (0.010) | 0.638 (0.010) |
| | Delicias | -0.019 (0.046) | 0.529 (0.012) | 0.522 (0.014) | 0.497 (0.009) | 0.482 (0.013) | 0.564 (0.008) | 0.550 (0.012) |
| | Tepatitlán | -0.027 (0.050) | 0.540 (0.014) | 0.573 (0.017) | 0.480 (0.012) | 0.481 (0.015) | 0.561 (0.010) | 0.599 (0.013) |
| | Cd.Obregón | -0.021 (0.051) | 0.483 (0.012) | 0.488 (0.015) | 0.493 (0.012) | 0.498 (0.015) | 0.548 (0.010) | 0.547 (0.013) |
| | Zaragoza | -0.019 (0.048) | 0.505 (0.013) | 0.509 (0.014) | 0.497 (0.012) | 0.500 (0.015) | 0.557 (0.012) | 0.567 (0.012) |
| CV2 | Celaya | 0.820 (0.001) | 0.824 (0.001) | 0.820 (0.003) | 0.824 (0.001) | 0.819 (0.003) | 0.830 (0.001) | 0.831 (0.003) |
| | Delicias | 0.771 (0.001) | 0.778 (0.001) | 0.770 (0.003) | 0.776 (0.001) | 0.769 (0.003) | 0.780 (0.001) | 0.770 (0.003) |
| | Tepatitlán | 0.773 (0.001) | 0.784 (0.001) | 0.813 (0.003) | 0.772 (0.001) | 0.769 (0.003) | 0.780 (0.001) | 0.810 (0.003) |
| | Cd.Obregón | 0.791 (0.001) | 0.787 (0.001) | 0.798 (0.003) | 0.787 (0.001) | 0.800 (0.003) | 0.792 (0.001) | 0.808 (0.004) |
| | Zaragoza | 0.757 (0.001) | 0.763 (0.001) | 0.769 (0.003) | 0.764 (0.001) | 0.768 (0.003) | 0.768 (0.001) | 0.782 (0.003) |
| ----- Days to maturity ----- | | | | | | | | |

| | | | | | | | | |
|--------------------------|------------|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| CV1 | Celaya | -0.047 (0.044) | 0.346 (0.014) | 0.320 (0.017) | 0.290 (0.014) | 0.258 (0.017) | 0.358 (0.013) | 0.336 (0.016) |
| | Delicias | -0.036 (0.040) | 0.524 (0.013) | 0.562 (0.011) | 0.535 (0.011) | 0.567 (0.011) | 0.606 (0.012) | 0.635 (0.011) |
| | Tepatitlán | -0.016 (0.038) | 0.092 (0.009) | 0.088 (0.021) | 0.086 (0.011) | 0.093 (0.022) | 0.090 (0.009) | 0.098 (0.024) |
| | Cd.Obregón | -0.038 (0.041) | 0.388 (0.017) | 0.405 (0.022) | 0.375 (0.012) | 0.419 (0.014) | 0.435 (0.014) | 0.466 (0.017) |
| | Zaragoza | -0.018 (0.040) | 0.423 (0.015) | 0.453 (0.017) | 0.384 (0.010) | 0.369 (0.014) | 0.457 (0.011) | 0.481 (0.014) |
| CV2 | Celaya | 0.643 (0.002) | 0.617 (0.003) | 0.544 (0.013) | 0.605 (0.003) | 0.531 (0.011) | 0.621 (0.003) | 0.547 (0.013) |
| | Delicias | 0.689 (0.001) | 0.729 (0.002) | 0.740 (0.006) | 0.721 (0.002) | 0.740 (0.005) | 0.738 (0.002) | 0.771 (0.005) |
| | Tepatitlán | 0.183 (0.001) | 0.183 (0.002) | 0.183 (0.008) | 0.178 (0.002) | 0.182 (0.005) | 0.178 (0.002) | 0.187 (0.006) |
| | Cd.Obregón | 0.653 (0.003) | 0.659 (0.003) | 0.630 (0.013) | 0.680 (0.003) | 0.673 (0.007) | 0.678 (0.003) | 0.667 (0.010) |
| | Zaragoza | 0.663 (0.001) | 0.674 (0.002) | 0.688 (0.005) | 0.670 (0.002) | 0.661 (0.005) | 0.677 (0.002) | 0.690 (0.006) |
| ----- Plant height ----- | | | | | | | | |
| CV1 | Celaya | -0.017 (0.040) | 0.431 (0.019) | 0.409 (0.023) | 0.414 (0.012) | 0.404 (0.016) | 0.459 (0.013) | 0.439 (0.018) |
| | Delicias | -0.016 (0.042) | 0.496 (0.017) | 0.535 (0.016) | 0.491 (0.011) | 0.499 (0.012) | 0.547 (0.012) | 0.578 (0.012) |
| | Tepatitlán | -0.014 (0.049) | 0.450 (0.023) | 0.492 (0.027) | 0.386 (0.014) | 0.370 (0.017) | 0.462 (0.015) | 0.508 (0.019) |
| | Cd.Obregón | -0.019 (0.037) | 0.470 (0.016) | 0.500 (0.014) | 0.476 (0.013) | 0.498 (0.014) | 0.523 (0.013) | 0.552 (0.013) |
| | Zaragoza | -0.024 (0.043) | 0.525 (0.018) | 0.555 (0.016) | 0.516 (0.012) | 0.547 (0.012) | 0.586 (0.014) | 0.617 (0.012) |
| | Celaya | 0.728 | 0.727 | 0.718 | 0.713 | 0.712 | 0.723 | 0.718 |

| | | | | | | | | | |
|-----|------------|---------|---------|---------|---------|---------|---------|---------|---------|
| CV2 | Delicias | (0.001) | (0.001) | (0.006) | (0.001) | (0.004) | (0.001) | (0.005) | |
| | | 0.789 | 0.792 | 0.821 | 0.786 | 0.793 | 0.794 | 0.822 | |
| | Tepatitlán | (0.001) | (0.001) | (0.003) | (0.001) | (0.002) | (0.001) | (0.003) | |
| | | 0.691 | 0.704 | 0.741 | 0.684 | 0.678 | 0.695 | 0.733 | |
| | Cd.Obregón | (0.001) | (0.001) | (0.007) | (0.001) | (0.005) | (0.001) | (0.007) | |
| | | 0.808 | 0.804 | 0.817 | 0.810 | 0.811 | 0.812 | 0.826 | |
| | Zaragoza | (0.001) | (0.001) | (0.004) | (0.001) | (0.003) | (0.001) | (0.004) | |
| | | 0.813 | 0.818 | 0.841 | 0.823 | 0.837 | 0.826 | 0.854 | |
| | | | (0.001) | (0.001) | (0.003) | (0.001) | (0.003) | (0.001) | (0.003) |

Supplementary Table 3: Pair-wise correlation between the observed and predicted values for days to anthesis for four models; L=line, E=site, G=genotypic information, A=pedigree, W=environmental variables. Values from one site (training site) were used to predict a second site (testing site).

| Genomic Model | Testing site | Training site | | | | |
|----------------|--------------|---------------|----------|------------|------------|----------|
| | | Celaya | Delicias | Tepatitlán | Cd.Obregón | Zaragoza |
| L+E+W | Celaya | --- | 0.684 | 0.725 | 0.713 | 0.715 |
| | Delicias | 0.684 | --- | 0.661 | 0.683 | 0.678 |
| | Tepatitlán | 0.727 | 0.660 | --- | 0.702 | 0.616 |
| | Cd.Obregón | 0.713 | 0.683 | 0.701 | --- | 0.668 |
| | Zaragoza | 0.714 | 0.678 | 0.613 | 0.665 | --- |
| E+W+G | Celaya | --- | 0.709 | 0.738 | 0.736 | 0.740 |
| | Delicias | 0.705 | --- | 0.673 | 0.719 | 0.707 |
| | Tepatitlán | 0.745 | 0.683 | --- | 0.730 | 0.640 |
| | Cd.Obregón | 0.708 | 0.700 | 0.705 | --- | 0.680 |
| | Zaragoza | 0.727 | 0.700 | 0.626 | 0.690 | --- |
| E+W+A | Celaya | --- | 0.718 | 0.749 | 0.731 | 0.747 |
| | Delicias | 0.691 | --- | 0.684 | 0.713 | 0.708 |
| | Tepatitlán | 0.736 | 0.697 | --- | 0.714 | 0.636 |
| | Cd.Obregón | 0.710 | 0.718 | 0.708 | --- | 0.678 |
| | Zaragoza | 0.730 | 0.722 | 0.635 | 0.685 | --- |
| E+W+G+A | Celaya | --- | 0.712 | 0.741 | 0.738 | 0.741 |
| | Delicias | 0.695 | --- | 0.674 | 0.717 | 0.703 |
| | Tepatitlán | 0.739 | 0.688 | --- | 0.727 | 0.633 |
| | Cd.Obregón | 0.718 | 0.708 | 0.709 | --- | 0.680 |
| | Zaragoza | 0.730 | 0.709 | 0.626 | 0.692 | --- |

Supplementary Table 4: Pair-wise correlation between the observed and predicted values for days to maturity for four models; L=line, E=site, G=genotypic information, A=pedigree, W=environmental variables. Values from one site (training site) were used to predict a second site (testing site).

| Genomic Model | Testing site | Training site | | | | |
|----------------|--------------|---------------|----------|------------|------------|----------|
| | | Celaya | Delicias | Tepatitlán | Cd.Obregón | Zaragoza |
| L+E+W | Celaya | --- | 0.579 | 0.180 | 0.534 | 0.526 |
| | Delicias | 0.578 | --- | 0.132 | 0.592 | 0.590 |
| | Tepatitlán | 0.180 | 0.131 | --- | 0.137 | 0.154 |
| | Cd.Obregón | 0.534 | 0.591 | 0.138 | --- | 0.570 |
| | Zaragoza | 0.529 | 0.590 | 0.152 | 0.571 | --- |
| E+W+G | Celaya | --- | 0.562 | 0.203 | 0.531 | 0.528 |
| | Delicias | 0.653 | --- | 0.180 | 0.615 | 0.630 |
| | Tepatitlán | 0.172 | 0.128 | --- | 0.144 | 0.161 |
| | Cd.Obregón | 0.567 | 0.594 | 0.194 | --- | 0.591 |
| | Zaragoza | 0.569 | 0.598 | 0.224 | 0.587 | --- |
| E+W+A | Celaya | --- | 0.549 | 0.162 | 0.521 | 0.530 |
| | Delicias | 0.639 | --- | 0.180 | 0.596 | 0.632 |
| | Tepatitlán | 0.173 | 0.123 | --- | 0.146 | 0.153 |
| | Cd.Obregón | 0.583 | 0.604 | 0.200 | --- | 0.615 |
| | Zaragoza | 0.569 | 0.594 | 0.162 | 0.577 | --- |
| E+W+G+A | Celaya | --- | 0.576 | 0.195 | 0.529 | 0.536 |
| | Delicias | 0.648 | --- | 0.182 | 0.599 | 0.628 |
| | Tepatitlán | 0.178 | 0.130 | --- | 0.144 | 0.159 |
| | Cd.Obregón | 0.585 | 0.606 | 0.199 | --- | 0.601 |
| | Zaragoza | 0.575 | 0.602 | 0.205 | 0.576 | --- |

Supplementary Table 5: Pair-wise correlation between the observed and predicted values for plant height for four models; L=line, E=site, G=genotypic information, A=pedigree, W=environmental variables. Values from one site (training site) were used to predict a second site (testing site).

| Genomic Model | Testing site | Training site | | | | |
|----------------|--------------|---------------|----------|------------|------------|----------|
| | | Celaya | Delicias | Tepatitlán | Cd.Obregón | Zaragoza |
| L+E+W | Celaya | --- | 0.622 | 0.607 | 0.659 | 0.654 |
| | Delicias | 0.624 | --- | 0.552 | 0.758 | 0.764 |
| | Tepatitlán | 0.608 | 0.550 | --- | 0.626 | 0.643 |
| | Cd.Obregón | 0.660 | 0.756 | 0.625 | --- | 0.727 |
| | Zaragoza | 0.654 | 0.762 | 0.642 | 0.728 | --- |
| E+W+G | Celaya | --- | 0.629 | 0.607 | 0.665 | 0.652 |
| | Delicias | 0.654 | --- | 0.554 | 0.764 | 0.760 |
| | Tepatitlán | 0.636 | 0.561 | --- | 0.641 | 0.650 |
| | Cd.Obregón | 0.681 | 0.757 | 0.628 | --- | 0.717 |
| | Zaragoza | 0.686 | 0.770 | 0.648 | 0.735 | --- |
| E+W+A | Celaya | --- | 0.614 | 0.596 | 0.651 | 0.637 |
| | Delicias | 0.651 | --- | 0.553 | 0.755 | 0.762 |
| | Tepatitlán | 0.623 | 0.548 | --- | 0.622 | 0.640 |
| | Cd.Obregón | 0.692 | 0.759 | 0.632 | --- | 0.726 |
| | Zaragoza | 0.690 | 0.777 | 0.658 | 0.736 | --- |
| E+W+G+A | Celaya | --- | 0.626 | 0.608 | 0.661 | 0.652 |
| | Delicias | 0.656 | --- | 0.554 | 0.763 | 0.769 |
| | Tepatitlán | 0.633 | 0.554 | --- | 0.630 | 0.648 |
| | Cd.Obregón | 0.689 | 0.762 | 0.629 | --- | 0.730 |
| | Zaragoza | 0.690 | 0.772 | 0.649 | 0.735 | --- |

Supplementary Table 6: Correlation between the observed and predictive values of the leaving-one-site-out prediction problem (prediction of one site when all the other sites are used in the model). L=line, E=site, G=genotypic information, A=pedigree, W=environmental variables and the interactions.

| Site | Genomic model | | | | | | |
|-----------------------------|---------------|-------|----------|-------|----------|---------|---------------|
| | L+E+W | E+W+G | E+W+G+GE | E+W+A | E+W+A+AE | E+W+G+A | E+W+G+A+GE+AE |
| ----- Days to anthesis----- | | | | | | | |
| Celaya | 0.821 | 0.823 | 0.821 | 0.822 | 0.825 | 0.828 | 0.825 |
| Delicias | 0.772 | 0.778 | 0.764 | 0.776 | 0.777 | 0.779 | 0.764 |
| Tepatitlán | 0.774 | 0.779 | 0.779 | 0.772 | 0.772 | 0.778 | 0.778 |
| Cd.Obregón | 0.792 | 0.785 | 0.787 | 0.781 | 0.786 | 0.788 | 0.796 |
| Zaragoza | 0.758 | 0.761 | 0.756 | 0.763 | 0.759 | 0.766 | 0.758 |
| ----- Days to maturity----- | | | | | | | |
| Celaya | 0.647 | 0.612 | 0.640 | 0.603 | 0.594 | 0.611 | 0.632 |
| Delicias | 0.691 | 0.720 | 0.697 | 0.710 | 0.699 | 0.725 | 0.708 |
| Tepatitlán | 0.183 | 0.183 | 0.181 | 0.179 | 0.183 | 0.178 | 0.187 |
| Cd.Obregón | 0.656 | 0.655 | 0.653 | 0.674 | 0.673 | 0.674 | 0.641 |
| Zaragoza | 0.665 | 0.67 | 0.664 | 0.669 | 0.663 | 0.676 | 0.657 |
| ----- Plant height----- | | | | | | | |
| Celaya | 0.730 | 0.727 | 0.728 | 0.712 | 0.717 | 0.723 | 0.724 |
| Delicias | 0.790 | 0.789 | 0.788 | 0.784 | 0.787 | 0.792 | 0.791 |
| Tepatitlán | 0.694 | 0.698 | 0.695 | 0.685 | 0.688 | 0.692 | 0.689 |
| Cd.Obregón | 0.809 | 0.800 | 0.805 | 0.805 | 0.807 | 0.808 | 0.808 |
| Zaragoza | 0.814 | 0.816 | 0.805 | 0.818 | 0.809 | 0.822 | 0.799 |