Yield gap causation in sunflower: First results from a remote sensing approach

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ABSTRACT

- Yield gap (difference between the attainable yield of a crop in a given environment and the average yield achieved by farmers) assessment, and the identification of gap putative causes are important in the contexts of food security and research prioritization. The farmer's attainable yield gaps for all 8 sunflower producing regions of Argentina has been shown to exceed the expected floor value of 25% of average farmer yields, indicating a need for research aimed at narrowing the gap. Remote sensing allows the documentation of the dynamics of intermediate variables (pretaining to the crop and to its environment) that affect yield at geospatially specified sites. Here we report results obtained during the first year of a three-year project aimed at identifying putative causes of sunflower yield gaps using remote sensors.
- We compiled a geographic database combining information on crop management (dates of sowing & harvest, yield, previous crop, etc.), satellite data (NDVI, precipitation) for the previous crop, the inter-crop fallow and the target crop and weather stations (radiation, temperature max & min etc.) for geospatially defined fields of more than 30 ha in size (n =110) in two sunflower-growing regions (La Pampa [LP] and southwest of Buenos Aires [SWBA]). Frontier regression analysis was used to model the limiting relationship between yield and photosynthetically active radiation absorbed by the crops (APAR). APAR was estimated from normalized difference vegetation index (NDVI) and incident radiation data obtained from meteorological stations. Distances to the boundary function were calculated for each data point. Aditonally, a frontier regression analysis was also performed for the relationship between yield and seasonal rain using daily precipitation estimates derived from remotely sensed data.
- The yield vs. APAR relationship for the pooled data was significant and positive ($p<0.001$; $R2=0.46$), as was the frontier regression ($p<0.001$). When the frontier regression was performed separately for each region, ranges of APAR and yield differed between regions but the slopes did not. In both cases, many data points fell below the boundary function. This framework allows yield variation to be considered in two dimensions, one related to resource capture (APAR) and the other to efficiency of resource usage (yield difference from the data point to the boundary function). The boundary function for the yield vs seasonal rain relationship ($p<0.001$) for the pooled data had a similar slope to that of a published limiting water productivity function for sunflower, and many data points fell below this boundary function. We tested the associations between some candidate gap causes and variations in crop seasonal APAR, seasonal rain and data point yield difference to the frontier regression, as illustrated in the following examples. The variation in seasonal APAR (i.e., resource capture), was related to the duration of the crop cycle in the LP region ($p<0.001$; $R2=0.22$), but not in the SWBA region ($p=0.192$); and seasonal APAR was strongly associated with maximum interception achieved by the crop in the SWBA region ($p<0.001$; $R2=0.63$) but the relationship was much weaker in the LP region ($p=0.03$;$R2=0.07$). Vertical distances to the yield vs. APAR frontier (i.e., efficiency of resource use) were negatively associated with maximum temperature during the critical period for grain number determination in both in the LP ($p<0.001$;$R2=0.22$) and SWBA regions ($p=0.06$;$R2=0.31$). Vertical distances to the yield vs. seasonal rain frontier were negatively correlated with accumulated precipitation up to flowering in LP ($p<0.001$;$R2=0.22$), but not in SWBA ($p=0.67$).
- Remote sensing, combined with management information, can be used to generate yield vs. APAR and yield vs. seasonal rain boundary functions and these functions can be used to assess performance yields) of individual fields in terms of resource capture and resource use efficiency. These analytical templates will allow us to identify regionally- (and annually-) specific hierarchies of dominant yield gap-causing factors, leading to regionally specific research prioritization of gap-reducing experimentation.
- To our knowledge, this is the first report for any grain crop in which remote sensing of the dynamics of crop NDVI and that of key crop environment variables has been combined with management information to provide a basis for quantifying yield gap determinants and establishing their inter-regional and inter-annual hierarchies.

Keywords: YIELD GAP, REMOTE SENSING, GIS, FRONTIER ANALYSIS

INTRODUCTION

Yield gap (difference between the attainable yield of a crop in a given environment and the average yield achieved by farmers) assessment, and the identification of gap putative causes are important in the contexts of food security and research prioritization. The farmer's attainable yield gaps for all 8 sunflower producing regions of Argentina has been shown to exceed the expected floor value of 25% of average farmer yields, indicating a need for research aimed at narrowing the gap (A. Hall Pers. Com.). Significantly more food could be produced with current crops if new ways are found to close the yield gap.

Currently there is great interest in measuring the yield gap and studying its determinants (Lobell, Cassman, & Field, 2009). There are many many attempts in literature to characterize the Yield gap for different crops, but none explicitly considers the spatial heterogeneity in yield gap causes. On the other hand, methods to bring actual yields to the potentials are highly site-specific (Godfray et al., 2010). Yield gap is commonly attributed to better soil or management conducted at the experimental stations where potential yields are characterized, but the specific reasons are often unknown due to lack of measurements that include the heterogeneity of the region under study (Lobell, Ortiz-monasterio, Addams, & Asner, 2002). It is important then to study the yield gap for different productive regions (spatial variation) and analyze the main factors that determines it.

Remote sensing allows us to obtain estimates of intermediate variables important for crop yield in a spatially explicit manner and with high temporal frequency. For example; photosynthetically active radiation absorbed by crops can be estimated from spectral indices derived from remote sensors. There are many studies in the literature where spectral indices are used to estimate yield at different spatial scales (Moriondo et al. 2007; Wang et al. 2010). Precipitation can also be monitored using remote sensing. The Tropical Rainfall Measuring Mission (TRMM) was tested in the Rio de la Plata basin with satisfactory results (Su, Hong, & Lettenmaier, 2008). Here we report results obtained during the first year of a three-year project aimed at identifying putative causes of sunflower yield gaps using remote sensors.

MATERIALS AND METHODS

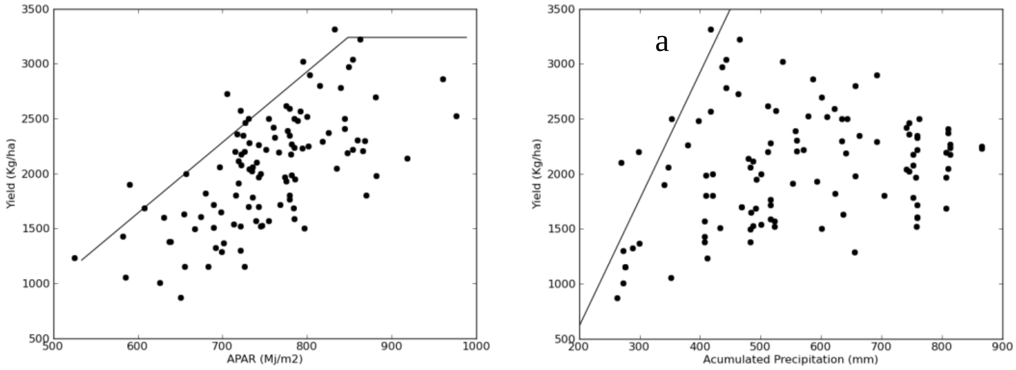
We compiled a geographic database combining information on crop management for fields of more than 30 ha in size (n =110) in two sunflower-growing regions (La Pampa [LP] and southwest of Buenos Aires [SWBA]). For each field we gathered information regarding planting date, harvest date, crop predecessor, management information, etc., flowering date, and critical period for each field was calculated using thermal degree units. We also georeferenced the perimeter of the lot. Using the National Weather Service stations (SMN) and climatic data sets provided by the Ministry of Agriculture (MINAGRI), point interpolation for daily data was performed for the entire study region of the variables maximum temperature, minimum temperature and solar radiation. The information was assembled into a geographic database.

Satellite data (MODIS-NDVI and TRMM - precipitation) was gathered for the previous crop, the inter-crop fallow and the target crop. Photosynthetically active radiation absorbed by the crops (APAR) was estimated from normalized difference vegetation index (NDVI) obtained from MODIS-terra product MOD13q1 (Lpdaac) and solar incident radiation data obtained from Weather Service stations (SMN). APAR was calculated according to Monteith (1972) model. Similarly the precipitation was extracted from the TRMM-3B42 daily product (Gsfc), for each fields we calculated the cumulative rainfall during the cycle, the accumulated precipitation up to flowering and the precipitation during the critical period.

Frontier regression analysis was used to model the limiting relationship between yield and photosynthetically active radiation absorbed by the crops (APAR). Frontier regression analysis was also performed for the relationship between yield and seasonal rain using daily precipitation estimates derived from remotely sensed data. For APAR vs yield relationship the variation was decomposed into two axes that representing the variation in resource capture radiation (variation in the APAR axis) and the use efficiency of harvested resources (distance from the frontier). For the relationship between accumulated rainfall vs yield we also decomposed the variation in use efficiency of captured resources (distance to the frontier). We tested the associations between some candidate gap causes and variations in crop seasonal APAR, seasonal rain and data point yield difference to the frontier regression. This framework allows yield gap variation to be considered in two dimensions, one related to resource capture (APAR) and the efficiency of resource usage (yield difference from the data point to the boundary function).

RESULTS

The yield vs. APAR relationship for the pooled data was significant and positive ($p<0.001$; $R2=0.46$), as was the frontier regression ($p<0.001$). When the frontier regression was performed separately for each region, ranges of APAR and yield differed between regions but the slopes did not. In both cases, many data points fell below the boundary function. The boundary function for the yield vs seasonal rain relationship ($p<0.001$) was significant for the pooled data and had a similar slope to that of a published limiting water productivity function for sunflower, and many data points fell below this boundary function (Fig 1).



a

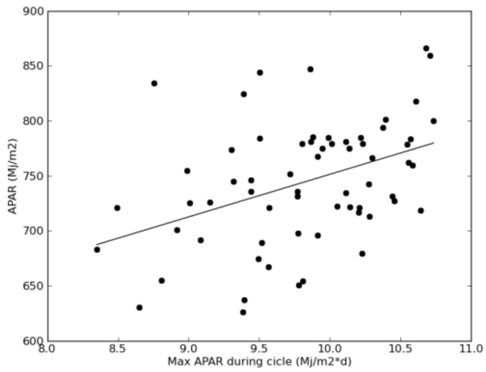
b

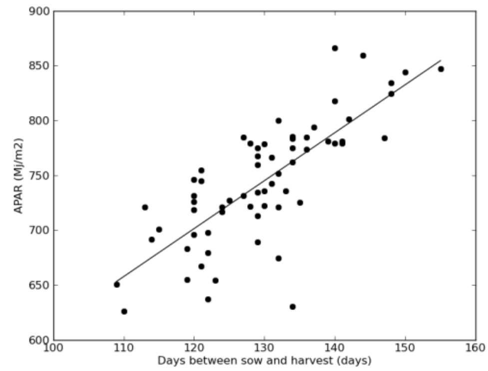
Fig 1. Frontier regressions for APAR vs yield. Yield = 6.54 * APAR – 1992.43 for APAR < 875 Mj/m2 (a) and seasonal rain from sowing to harvest vs yield. Yield = 11.47 * Seasonal rain – 1631. 58 for seasonal rain < 450 mm (b).

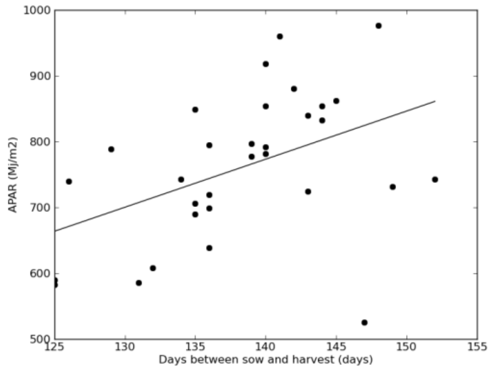
The variation in seasonal APAR (i.e., resource capture), was related to the duration of the crop cycle in the LP region ($p<0.001$; $R2=0.22$), but not in the SWBA region ($p=0.192$); and seasonal APAR was strongly associated with maximum interception achieved by the crop in the SWBA region ($p<0.001$; $R2=0.63$) but the relationship was much weaker in the LP region ($p=0.03$;$R2=0.07$)(Fig. 2) .

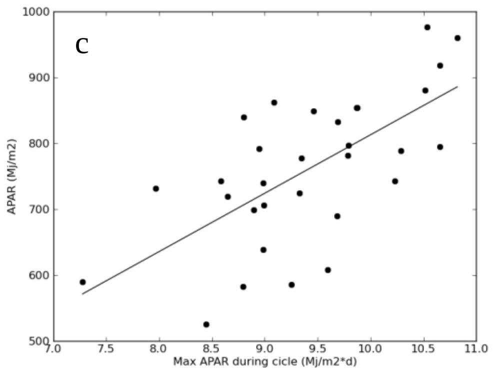
a

b









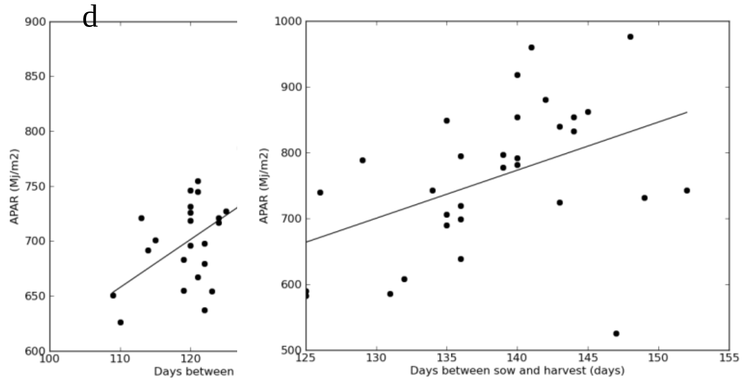
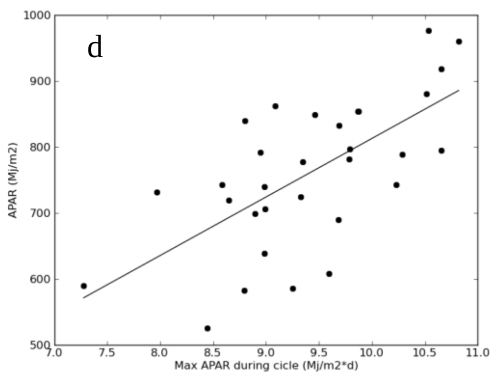
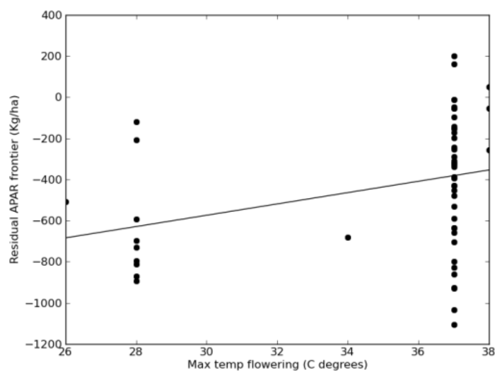


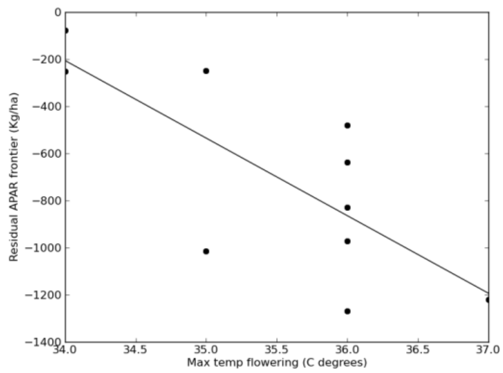
Fig 2. Days between sow and harvest and Max APAR during cycle relationship with variation in seasonal APAR (i.e., resource capture) for LP (a, c) and SWBA regions (c,d).

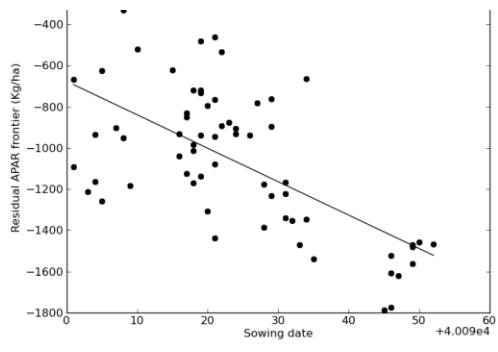
c

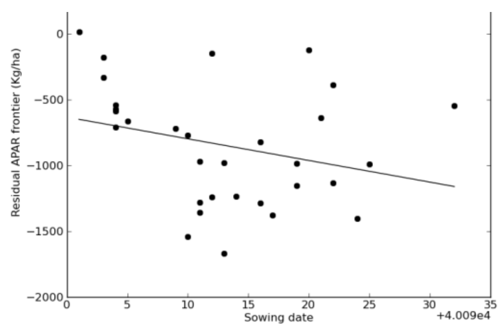


Vertical distances to the APAR frontier (i.e., efficiency of resource use) were associated with maximum temperature during the critical period for grain number determination in SWBA region (p=0.01;R2=0.56) but the relation was weaker in the LP (p<0.02;R2=0.09) (fig 3). Vertical distance to the APAR frontier was also related to seasonal precipitation in the LP region (p <0.0001, R2 =





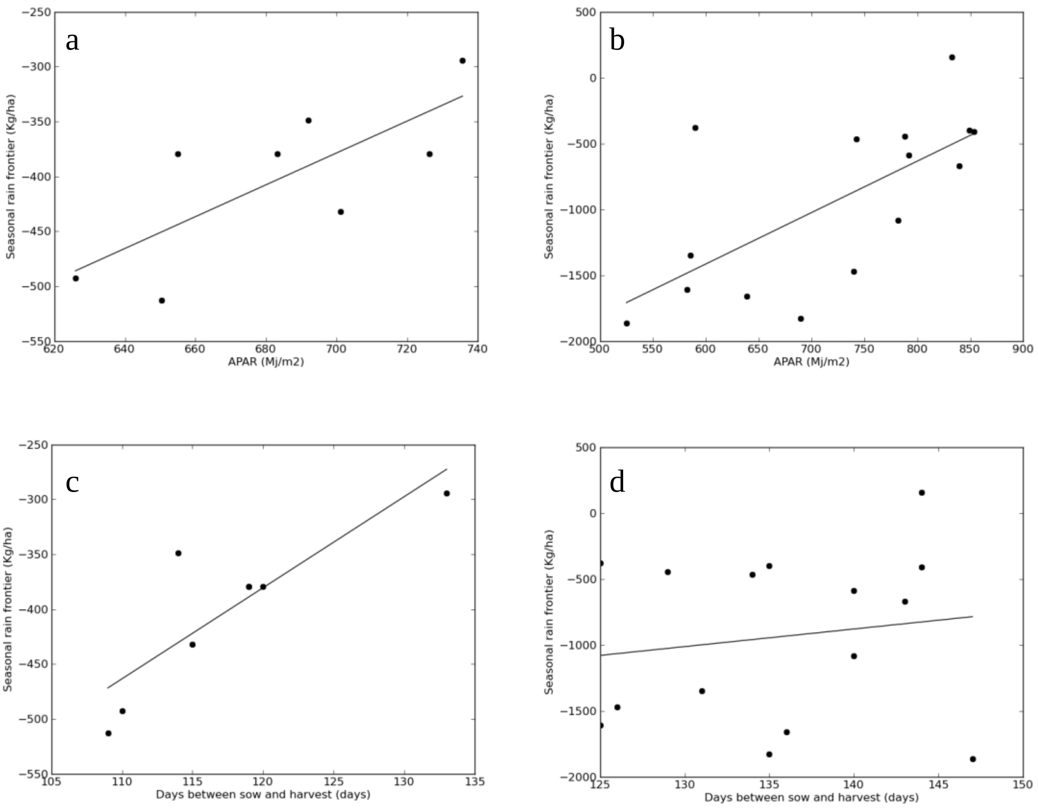




0.3) but not for SWBA (p = 0.54). Similarly, the distance from the APAR frontier was related to planting date in LP region (p<0.0001, R2 = 0.39) but was not related in the SWBA region (p = 0.12).

Fig 3. Max temperature during flowering and Sowing date relationship with distance from APAR frontier (i.e., resource use efficiency) for LP (a, c) and SWBA regions (c,d).

Regarding to use efficiency of the seasonal rain, vertical distances to rain frontier were negatively correlated with accumulated precipitation up to flowering in LP (p<0.001;R2=0.22), but not in SWBA (p=0.67). Similarly, the residuals of the seasonal rain frontier vs. APAR were positively related to APAR in LP (r = 0.75, p = 0.03) as in the SWBA region (r = 0.67, p = 0.005). The relationship between distance to seasonal rain frontier and cycle length was significant and positive in the LP region (r = 0.85, p =0.006) but was not significant in the SWBA region (p = 0.5)(fig 4).



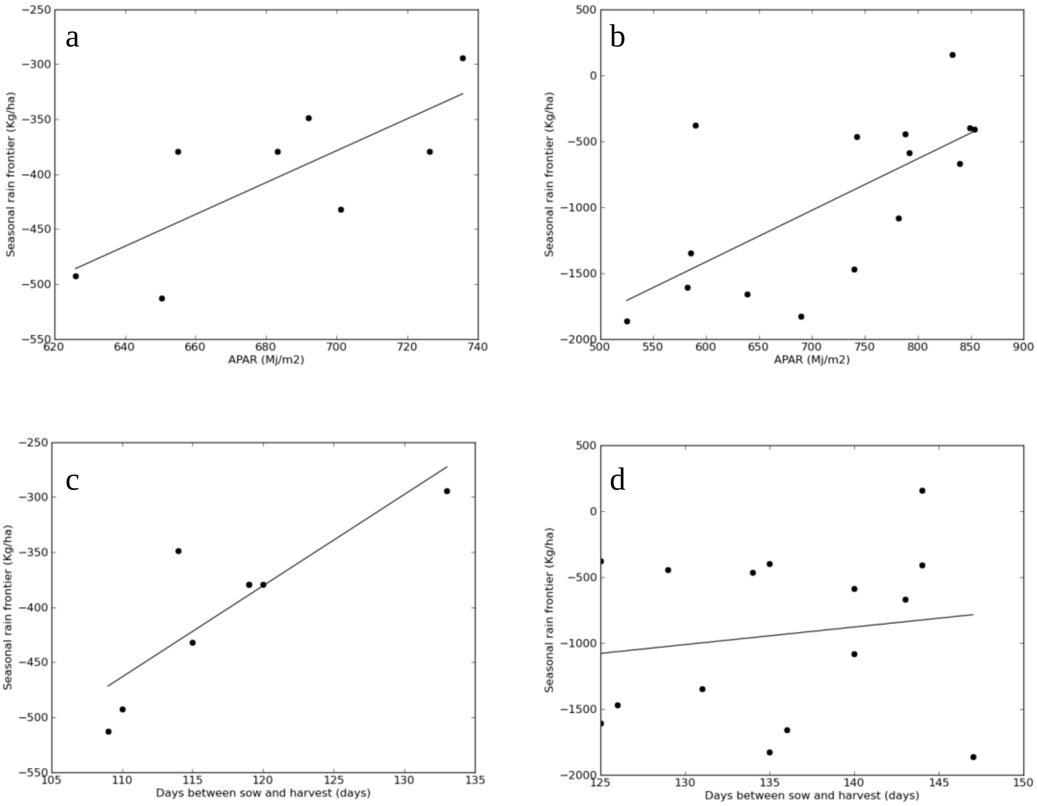


Fig 4. APAR and Days between sow and harvest relationship with distance from seasonal rain frontier (i.e., resource use efficiency) for LP (a, c) and SWBA regions (c,d).

DISCUSION

Remote sensing, combined with management information, can be used to generate yield vs. APAR and yield vs. seasonal rain boundary functions and these functions can be used to assess performance yields of individual fields in terms of resource capture and resource use efficiency. The variation of resource capture APAR and the variation in use efficiency of captured resources represented by the residuals of APAR and seasonal rain frontiers were different among regions. For every region in this particular year we could identify key environmental and managerial variables related with capture and usage of APAR and seasonal rain resources.

These analytical templates will allow us to identify regionally- (and annually-) specific hierarchies of dominant yield gap-causing factors, leading to regionally specific research prioritization of gap-reducing experimentation. To our knowledge, this is the first report for any grain crop in which remote sensing of the dynamics of crop NDVI and that of key crop environment variables has been combined with management information to provide a basis for quantifying yield gap determinants and establishing their inter-regional and inter-annual hierarchies.

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REFERENCES

Gsfc (Goddadrd Space Flight Center), http://trmm.gsfc.nasa.gov

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science (New York, N.Y.)*, *327*(5967), 812-8. doi:10.1126/science.1185383

Lpdaac (Land Processes Distributed Active Archive Center), http://lpdaac.usgs.gov

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources*, *34*(1), 179-204. doi:10.1146/annurev.environ.041008.093740

Lobell, D. B., Ortiz-monasterio, J. I., Addams, C. L., & Asner, G. P. (2002). Soil, climate, and management impacts on regional wheat productivity in Mexico from remote sensing. *Agricultural and Forest Meteorology*, *114*, 31-43.

MINAGRI (Ministerio de Agricultura, Ganadería y Pesca), http://www.minagri.gob.ar

Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology*, *9*, 747-766.

Moriondo, M., Maselli, F., & Bindi, M. (2007). A simple model of regional wheat yield based on NDVI data. *European Journal of Agronomy*, *26*(3), 266-274. doi:10.1016/j.eja.2006.10.007

SMN (Servicio Meteorológico Nacional), http://www.smn.gov.ar

Su, F., Hong, Y., & Lettenmaier, D. P. (2008). Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and Its Utility in Hydrologic Prediction in the La Plata Basin. *Journal of Hydrometeorology*, *9*(4), 622. doi:10.1175/2007JHM944.1

Wang, Y.-P., Chang, K.-W., Chen, R.-K., Lo, J.-C., & Shen, Y. (2010). Large-area rice yield forecasting using satellite imageries. *International Journal of Applied Earth Observation and Geoinformation*, *12*(1), 27-35. doi:10.1016/j.jag.2009.09.009