Title of Grant / Cooperative Agreement:	Crop yield assessment and mapping by a combined use of Landsat-8, Sentinel-2 and Sentinel-1 images
Type of Report:	Summary of Research
Name of Principal Investigator:	Sergii Skakun
Period Covered by Report:	Feb 01, 2018 - Jan 31, 2021
Name and Address of recipient's institution:	University of Maryland, 3112 Lee Bldg. 7809 Regents Dr, College Park MD 20742
NASA Grant / Cooperative Agreement Number:	80NSSC18K0336

Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Have any Subject Inventions / New Technology Items resulted from work performed under this Grant / Cooperative Agreement?	No ◉	Yes ○
If yes a complete listing should be provided here: Details can be provided in the body of the Summary of Research report.		

Reference 14 CFR § 1260.27 Equipment and Other Property (abbreviated below)
A Final Inventory Report of Federally Owned Property, including equipment where title was taken by the Government, will be submitted by the Recipient no later than 60 days after the expiration date of the grant. Negative responses for Final Inventory Reports are required.

Is there any Federally Owned Property, either Government Furnished or Grantee Acquired, in the custody of the Recipient?	No ◉	Yes ○
If yes please attach a complete listing including information as set forth at § 1260.134(f)(1).		

Attach the Summary of Research text behind this cover sheet.

Reference 14 CFR § 1260.22 Technical publications and reports (December 2003)
Reports shall be in the English language, informal in nature, and ordinarily not exceed three pages (not counting bibliographies, abstracts, and lists of other media).

A Summary of Research (or Educational Activity Report in the case of Education Grants) is due within 90 days after the expiration date of the grant, regardless of whether or not support is continued under another grant. This report shall be a comprehensive summary of significant accomplishments during the duration of the grant.

“Crop yield assessment and mapping by a combined use of Landsat-8, Sentinel-2 and Sentinel-1 images”

Final report

PI: Sergii Skakun

Period: Feb 01, 2018 to Jan 31, 2021

Address: 3112 Lee Bldg. 7809 Regents Dr, College Park MD 20742

Grant number: 80NSSC18K0336

Accomplishments

The *overall scientific goal* of the project was to develop a new algorithm and products for agriculture monitoring, namely crop yield assessment and mapping, by combining moderate spatial resolution images acquired by Landsat-8, Sentinel-2 and Sentinel-1/SAR remote sensing satellites. The project explored an increased temporal frequency of observations and coverage as well as combination of optical and microwave (SAR) imagery to generate new products that provided improved spatially explicit crop yield mapping at regional and field scales. The project was focused on three major crops, namely wheat, corn and soybeans, that are within the top 6 major commodities in the world and account for 25% of global crop production.

Key highlights:

- Multi-spectral satellite data can be used to assess crop yield at regional to field scale
- Performance is dependent on data frequency, spatial resolution, and spectral bands
- Temporal frequency and spatial resolution of satellite data are critical for explaining yield variability at field scale
- Green, red edge and NIR were the most important in explaining corn and soybean yields; red and NIR for wheat yeilds.

Key results:

- In order to provide in-season winter crop maps at moderate spatial resolution (30 m), we implemented an automatic approach (Gaussian Mixture Model – GMM) (Skakun et al., 2019), which was previously developed for MODIS and prototyped for Landsat 8 and Sentinel-2. The approach uses a phenological metric during a green up stage of winter crop development, and that is why a frequent satellite data record is extremely important. We used the NASA Harmonized Landsat Sentinel-2 (HLS) product. The winter crop maps were generated for 2016-2019 in Ukraine at regional scale. The combined use of Landsat 8/Sentinel-2 allowed us to improve the coefficient of determination 2.5 and 1.04 times, compared to Landsat 8 and Sentinel-2 only, respectively, when comparing to official statistics areas.
- Optical satellite imagery has non-unform coverage due to the cloud/shadow areas and limited swath. Therefore, the number of valid observations will be varying and would influence the crop yield model. Therefore, we proposed a new approach to normalize satellite imagery (both vegetation indices and surface reflectance) through phenological fitting against accumulated growing degree days (AGDD). We used a quadratic function that showed to adequately describe the crop phenology against AGDD. We implemented an efficient code in Python through array operations.
- We developed an empirical crop yield model that unlike previous studies incorporated directly surface reflectance from HLS data. We implemented two modes: a linear model with regularization and non-linear Gaussian Process model. When implementing for winter wheat yield mapping in Ukraine, the non-linear model showed a slightly better performance (RMSE=0.237t/ha against 2.42 t/ha). That models were used to map winter wheat yields at regional scale in Ukraine.

- Based on uncertainties of calibration data (that come usually from official statistics) and satellite-based model, we have established a specification for uncertainty estimation for winter wheat yield estimates: 0.06+0.06*yield [t/ha]. This was done for the first and emphasizes the use of uncertainties in yield estimation.
- While optical satellite imagery is impacted by cloud cover, images acquired by synthetic aperture radar (SAR) sensors (Sentinel-1) operating at microwave range are not. Therefore, we explored combination of optical and SAR data for crop yield assessment. As a common parameter for the optical-SAR combination, a DVI index was selected. We found that DVI can be extracted from SAR data with an error ~0.04 (with typical DVI values ranging from 0.05 to 0.5).
- As part of the cropland mapping efforts, we investigated the effect of the military conflict in Eastern Ukraine on croplands (Skakun et al., 2019). The military conflict in the Donetsk and Luhansk regions of Ukraine, which started in 2014, has led to the decline of industrial production and the relative increased role of agriculture in the regional economy. As the conflict has been impacting agricultural areas, which account for almost fifty percent of the two regions, we used satellite imagery to quantify agricultural land use changes between 2013 and 2018. Our results show that, while areas under control of the Ukrainian Government did not experience net cropland losses, the areas under control of militants experienced almost 22% decrease in cropland areas in 2018 as compared to 2013. The majority of the losses were due to land abandonment, exhibiting a return to natural vegetation.
- Corn and soybean yield assessment at field scale in USA:
    - First, we explored the effect of spatial resolution on yield variability. We found that reducing spatial resolution from 3 m to 30 m reduced yield variance at field scale with relative efficiency decreasing from 1.0 to 0.6, therefore decreasing capabilities of capturing within-field yields with moderate spatial resolution sensors. At the same time, the variance of yields inside 10, 20, or 30 m pixels increased up to 20%. These results are consistent with previous recommendations established within the VALERI protocol to validate coarse and moderate resolution remote sensing products and have implications on collecting ground-based crop yields, for example, through crop cuts. When validating coarse (100 m–1 km) and moderate (10–30 m) resolution crop yield maps, one must ensure that variability inside the pixel is captured through multiple (10–15) point-based samples.
    - In order to detect the optimal timing of correlating satellite-derived features with corn and soybean yields, a high temporal resolution of satellite data was required. This was achieved through the use of near-daily Planet data and a combination of 3–5 day revisit cycles of Sentinel-2 and Landsat 8 combined. The maximal correlations for corn and soybean were obtained at 3 and 2–2.5 months, respectively, which is consistent with previous studies utilizing coarse resolution MODIS data and county-level yields. We observed a very variable performance of these datasets to explain within-field yield variability: coefficient of determination R^2 varied from 0.21 to 0.88 (average 0.56±0.19) for 30 m HLS and from 0.09 to 0.77 (0.30±0.16) for 3 m Planet.
    - The maximal correlation between satellite-derived features and yields was observed 2–3 months before the harvest, therefore potentially enabling yield forecasts at field scale end of July to mid-August. We also found that performance of the satellite-derived models was better for corn and soybean fields with lower average yields: as the yields increase, R^2 values decrease. It means that multi-spectral data saturate over high yields and cannot capture yield variability.
    - The maximal correlation between satellite-derived features and yields was observed 2–3 months before the harvest, therefore potentially enabling yield forecasts at field scale end of July to mid-August. We also found that performance of the satellite-derived models was better for corn and soybean fields with lower average yields: as the yields increase, R^2 values

decrease. It means that multi-spectral data saturate over high yields and cannot capture yield variability.
    - In terms of spectral bands, green (~0.560 μm) and NIR (~0.865 μm) were the most important for Planet and HLS to explain corn and soybean within-field yield variability. When analyzing WV-3 data (at 1.25 m spatial resolution), red-edge (0.726 μm) showed to be the most important in explaining yield variability. Overall, SR-based models outperformed VI-based models highlighting the importance of incorporating SR values directly into the yield models
- Fundamental results were achieved, when simulating crop spectra depending on their traits that influence productivity, through radiative transfer (PROSAIL model) (Gitelson et al., 2021). The proper modelling of the radiative transfer in canopies with the unique green LAI vs. canopy [Chl] (CCC) relationships requires a unique combination of modeling parameters, specifically leaf [Chl] and green LAI, which, to the best of our knowledge, has not yet been considered. We run various simulations and empirically constraints the LAI/CCC relationships to match the in-situ ones. Our results showed that without such a constraints, simulation would not correspond to ground observations. These results emphasized the necessity for including within-leaf anatomical structure, together with the use of realistic combinations of input parameters, specifically green LAI and leaf chlorophyll content, in integrated canopy reflectance models. These are crucial for the successful application of generic spectral methods to a wide range of plant species with different traits (e.g., C3, C4, monocot, dicot, erectophile, planophile, etc.).
- We analyzed VHR data for cropland mapping in Africa. Planet data at 3 m spatial resolution were very useful in mapping smallholder fields in Uganda. Fields are of small size, fragmented and mixed, therefore when using moderate spatial resolution at 30 m resolution will lead to biases in area estimates, and consequently to biases in production estimation. Having near-daily Planet data allows us to capture crop phenology, map croplands and estimate areas.

Dissemination of results

Peer-reviewed publications in journals:

1. Hall, J.V., Zibtsev, S.V., Giglio, L., Skakun, S., Myroniuk, V., Zhuravel, O., Goldammer, J. G., Kussul, N. (2021). Environmental and Political Implications of Underestimated Cropland Burning in Ukraine. **Environmental Research Letters** (in revision)
2. Skakun, S., Kalecinski, N.I., Brown, M.G.L., Johnson, D.M., Vermote, E.F., Roger, J.-C., & Franch, B. (2021). Assessing within-Field Corn and Soybean Yield Variability from WorldView-3, Planet, Sentinel-2, and Landsat 8 Satellite Imagery. **Remote Sensing**, *13*, art. num. 872.
3. Gitelson, A., Arkebauer, T., Viña, A., Skakun, S., & Inoue Y. (2021). Evaluating plant photosynthetic traits via absorption coefficient in the photosynthetically active radiation region. **Remote Sensing of Environment**, *258*, art. num. 112401.
4. Kussul, N., Lavreniuk, M., Kolotii, A., Skakun, S., Rakoid, O., & Shumilo, L. (2020). A Workflow for Sustainable Development Goals Indicators Assessment Based on High Resolution Satellite Data. **International Journal of Digital Earth**, *13*(2), 309–321.
5. Skakun, S., Justice, C. O., Kussul, N., Shelestov, A., & Lavreniuk, M. (2019). Satellite data reveal cropland losses in South-Eastern Ukraine under military conflict. **Frontiers in Earth Science**, 7, art. num. 305.
6. Skakun, S., Vermote, E., Franch, B., Roger, J. C., Kussul, N., Ju, J., & Masek, J. (2019). Winter Wheat Yield Assessment from Landsat 8 and Sentinel-2 Data: Incorporating Surface Reflectance, Through Phenological Fitting, into Regression Yield Models. **Remote Sensing**, 11(15), art. num. 1768.
7. Franch, B., Vermote, E. F., Skakun, S., Roger, J. C., Becker-Reshef, I., Murphy, E., & Justice, C. (2019). Remote sensing based yield monitoring: Application to winter wheat in United States and Ukraine. **International Journal of Applied Earth Observation and Geoinformation**, *76*, 112–127.

Results of the project were included into the NASA report on “**Commercial SmallSat Data Acquisition Program Pilot. Evaluation Report**” (https://cdn.earthdata.nasa.gov/conduit/upload/14180/CSDAPEvaluationReport_Apr20.pdf).

Presentation of results on scientific symposiums, conferences, and workshops:

- Skakun, S., 2020. “Crop yield assessment and mapping by a combined use of Landsat-8, Sentinel-2 and Sentinel-1 images”. **Land Cover Land Use Change (LCLCU) Science Team Meeting**. 10/19/2020 to 10/21/2020 (*online*)
- Skakun, S., 2020. “Capturing Corn and Soybean Yield Variability at Field Scale Using Very High Spatial Resolution Satellite Data”. **2020 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2020)**, 26 September – 2 October, 2020 (*online*)
- Ghazaryan G., Skakun S., König S., Rezaei E., Siebert S., Dubovyk O. 2020. Crop Yield Estimation using Multi-Source Satellite Image Series and Deep Learning. **2020 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2020)**, 26 September – 2 October, 2020 (*online*)
- Ghazaryan, G., Skakun, S., König, S., Eyshi Rezaei, E., Siebert, S., & Dubovyk, O. (2020, May). “Crop Yield Estimation Using Multi-source Satellite Image Series and Deep Learning”. In **EGU General Assembly Conference Abstracts** (p. 13957). (*online*)
- Skakun, S., 2020. “Very high spatial resolution satellite data for agricultural monitoring”. **IAMO Forum 2020 “Digital transformation – towards sustainable food value chains in Eurasia”**, 24-26 June 2020 (*online*)
- Vermote, E., Franch, B., Skakun, S., Becker-Reshef, I., & Justice, C. (2020, January). Agricultural Remote-Sensed Yield Algorithm (ARYA): Application to Major Winter Wheat Exporting Countries (Invited Presentation). In **100th American Meteorological Society Annual Meeting**. AMS.
- Santamaria-Artigas, A. E., Skakun, S., Franch, B., Roger, J. C., & Vermote, E. (2020, January). Agricultural monitoring from combined optical and SAR data. In **100th American Meteorological Society Annual Meeting**. AMS
- Skakun, S., Roger, J. C., & Vermote, E., 2019. “Analysis of corn and soybean yield variability at field scale using VHR satellite data”. In **AGU Fall Meeting 2019**. AGU. (*poster*)
- Skakun S. *et al.,* 2019. “Analysis of corn and soybean yield variability at field scale using VHR satellite data”, **IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2019**, July 28 – August 2, 2019, Yokohama, Japan (*oral*)
- Skakun S., *et al.*, 2019. “Crop yield assessment and mapping by a combined use of Landsat-8, Sentinel-2 and Sentinel-1 images”, **NASA Harvest Annual Meeting**, June 24–26, 2019, Washington, DC (*oral*)
- Santamaria-Artigas A., Skakun S., Franch B., Roger J.-C., and Vermote E., 2019. “Agricultural monitoring from optical and SAR data”, **JpGU 2019 Japan Geoscience Union (JpGU) 2019 Conference** (May 26–30, 2019) in Chiba, Japan (*poster*)
- Skakun S. *et al.*, 2019. “Winter wheat yield assessment from Landsat 8 and Sentinel-2 data: why data normalization matters”, **ESA Living Planet Symposium**, May 13–17, 2019, Milan, Italy (*poster*)
- Skakun S. *et al.*, 2019. “Crop Yield Assessment and Mapping by a Combined use of Landsat, Sentinel 2 and Sentinel 1”, **2019 NASA LCLUC Spring Science Team Meeting**, April 9–11, 2019, Rockville MD, USA (*oral*)

- Skakun S., 2018. “Application of harmonized Landsat Sentinel-2 product for crop yield assessment”, **6th International Conference GEO-UA 2018 «Earth observations for sustainable development and security»**, 18-19 September 2018, Kyiv, Ukraine (*oral*)
- Skakun S., Franch B., Vermote E., Roger J.-C., Justice C., Masek J., Murphy E., 2018. “Winter Wheat Yield Assessment Using Landsat 8 and Sentinel-2 Data”, **IEEE International Geoscience and Remote Sensing Symposium** (**IGARSS) 2018**, 22–27 July 2018, Valencia, Spain (*oral*)
- Skakun S., Franch B., Roger J.-C., Vermote E., Justice C., Masek J. (2018) “**Combined Use of Landsat-8 and Sentinel-2 Data for Agricultural Monitoring”,** Japan Geoscience Union (JpGU) 2018 Conference (May 20-24, 2018) in Tokyo/Chiba, Japan (*invited presentation*, *oral*)
- Skakun, S., Roger, J.-C., Vermote, E., Franch, B., Justice, C., & Masek, J., 2018. “Combined Use of Landsat-8 and Sentinel-2 Data for Agricultural Monitoring”, **Emerging Technologies and Methods in Earth Observation for Agricultural Monitoring**, USDA, February 13–15, 2018, Beltsville, MD, USA (*invited presentation, oral*)