**Predicting Food Security with Machine Learning**

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July 25, 2019

**Abstract**

Hunger is on the rise throughout Africa, with famine threatening millions in several countries. Identifying food insecurity crises rapidly and accurately can enable humanitarian responses to mitigate casualties from hunger and save lives. We develop a predictive model based on readily available, spatially granular data on prices, geography, and demographics. Using machine learning techniques, we are able to improve the accuracy of predicting those villages that face a potential threat of hunger. As with any rare event, one challenge with predicting food insecurity is the thankfully low rate of severe food insecurity in the baseline data; we use different approaches to address this imbalance. We apply our procedure to three sub-Saharan African countries: Malawi, Tanzania, and Uganda to predict food security in out-of-sample villages. We correctly identify 69-88 percent of the food insecure clusters, which is 10 - 90 percent higher than the baseline model using a logistic regression. We further explore which data splits perform best …Our result shows that a data-driven model with the help of machine learning methods can significantly improve its performance on capturing the food insecure households despite the imbalance in the data. Our paper demonstrates that this approach could be used in a scalable, automatically updated prediction model that could enhance the current famine early warning systems.

**Keywords:** food insecurity, machine learning, early warning, Sub-Saharan Africa, famine

**Predicting Food Security with Machine Learning**

1. **Introduction**

Hunger crises are increasing in frequency and severity in many parts of the world. Identifying the scale and scope of these crises in a timely and accurate fashion is essential for providing food aid and organizing humanitarian responses to mitigate the long-run effects of food insecurity. Without the information required to identify the right populations to target programming and resources, the food aid often fails to arrive the areas in time where the assistances are needed the most (Barrett and Headey 2014). One of the many reasons that prevent building a successful early warning system is that data are scarce, and data collection is costly (Hutchinson 1991). The data gap hinders the efforts to effectively target the population in need and calls for the use of data and method that are cost-effective and accurate. Currently, governments and NGOs in the sub-Saharan Africa region use the Integrated Food Security Phase Classification System (IPC) as the early warning system. The IPC uses a Delphic system that requires detailed on-the ground data, and is updated quarterly for each livelihood zones, making it difficult to identify specific villages that might be at risk of hunger in the near term.

The recent increase in available data related to geography, weather, and market price for food staples provides us with the opportunity to predict food security more frequently at a finer geographic level. Nightlights data (Chen and Nordhaus 2011; Henderson et al. 2012) can serve as a proxy for economic activity but variations in the nightlight intensity is too low in remote rural or better off urban areas to detect any substantial changes in economic outcomes. Mobile phone data (Blumenstock et al.,2015; Steele et al., 2017) also hold potential for identifying economic outcomes, and are more frequent and less expensive than census surveys. However, geocodes are often limited to cell towers, and the biases associated with using relying on cell phone-sourced information to infer population statistics are as of yet, not well understood. Very high-resolution satellite imagery is becoming cheaper but the lack of labelled data in the imageries makes it difficult to extract structured information from thee raw images (Engstrom et al., 2017; Donaldson and Storeygard, 2016). Recent studies using a Convolutional Neural Network (CNN) and transfer learning (Jean et al., 2016; Babenko et al. 2017) make promising progress utilizing the information in satellite imageries. These models can explain up to 60% - 75% of the variation at the village level wealth and asset measures in several sub-Saharan Africa countries. However, the reliance on the information in the satellite imagery (specifically, building size, roof type, road conditions) limits its performance for time varying development indicators. Head et al. (2017) finds that the prediction performance of the Jean et al method degrades quickly on health and nutrition outcomes to no better than random guessing in some cases. The reliance on nightlight data in this approach also limits the prediction accuracy when applied in countries with different socioeconomic conditions. The external validity and interpretability of this deep learning-based approach call for a method tailored for food security predictions.

To the best of our knowledge, Lentz et al. (2019) is one of the few papers that combines spatially and temporally granular data that are publicly available to predict the food security status that greatly improves the prediction accuracy without significant cost in data collection and model training. Building on the framework in Lentz et al. (2019), in this paper, we construct a prototype of an early-warning system that is automatically updated, generalizable, scalable, and cost-effective in predicting areas of potential food shortage. Like Lentz et al, we incorporate data of different sources, dimension, and scales into a single predictive model of food security status. We use machine learning models to predict cluster-level food security status for targeting, aid purposes in times of food shortage. Variables in the model include the market price of food staples, weather shocks in growing seasons, and geospatial features around clusters. We combine data techniques such as oversampling and data segmentation with the machine learning models to improve prediction performance on the food insecure categories specifically. The models correctly capture 69-88 % of food insecurity categories among the three countries for different food security measures. The main contribution of this paper is to improve the prediction of clusters with potential food crisis in an imbalanced data setting with spatial-temporal correlations in the data. We are able to achieve this by choosing the right measurement of model success, data sampling, data split and data segmentation.

Instead of predicting the overall accuracy of food security status in previous studies, this study focuses on correctly detecting the clusters that are actually food insecure. Similar to a fraud detection problem, severe food insecurity crises are rare but too valuable to miss, even for a single one of them. The failure of identifying villages with food shortage is more costly than falsely sending food assistance to areas that do not have a shortage of food. Therefore, we focus more on identifying all the insecure clusters to maximize the recall rate in classification, where the recall rate is defined as percent of actual insecure households correctly captured by the model. We care less about minimizing the number of secure clusters misclassified as unsafe. In technical terms, we put a higher weight on the recall rate than precision rate for classifying the food security categories. Choosing the right criterion to optimize matters for model selection and parameter tuning. Ultimately, we want the model to correctly detect the minority classes that are food insecure. This paper uses a cost-sensitive learning approach to maximize the recall without too much sacrifice on precision.

Along with choosing the optimization criterion, we also explore the effect of different up and down sampling approaches to identify the food insecure groups. Various sampling techniques are used to create a balanced data-set that forces the classifiers to learn about the characteristics of the minority class. One such method is merely oversampling the minority class at the risk of model overfitting. SMOTE creates synthetic new data of the minority class by forming convex combinations of neighboring points, as a way to reduce the overfitting in oversampling.

Data splits and data segmentation also matters to creating a balanced and representative training and testing data set, with more discussion in the methodology section.

As a natural extension to Lentz et al. (2019), this study expands the study areas to Malawi, Uganda, and Tanzania with more years of data to test the framework with more heterogeneity in geography, environment, and socioeconomic status. For example, Uganda has two growing seasons, and the main food staples are matoke and cassava while most areas in Malawi and Tanzania have only one growing season and rely on maize as the staple food. This means adjustments to the local climate and agricultural markets, such as having the weather variables during local growing seasons, grabbing markets data on the staples that take up a more significant share in the household budget in that specific area. The machine learning algorithms and data techniques used for prediction are the same kind for the three countries, but the hyperparameters are tuned on the training dataset of each country separately. This procedure makes the model generalizable for application in other data-scarce countries and areas with some previous household survey data (LSMS or DHS) and frequently updated market price for food staples. At the same time, the model remains flexible and adaptable enough to capture the differences between countries such as climate, crops, and road infrastructures. This research also sheds light on the ability to apply the model trained on areas where we have ground-truth data to offer insights on areas of the world where we have few survey data. We compare different methods and protocols of handling the raw data, choosing the right data split and data segmentation, selecting the optimal model, to come up with a standardized data flow that maximizes our chances of making the model generalizable for potentially other areas in the world.

This paper uses a data-driven framework with machine learning techniques to predict the onset of food crises. Combining remote sensing data with household surveys and price data, the models are able to produce the most spatially and temporally granular predictions of food security. With an emphasis on the structure of the prediction error, this paper uses various machine learning techniques to reduce the misclassification of food insecure cluster. The framework developed in this paper has important policy implications for accurately target and aid areas of potential food shortage in data scarce environments.

1. **Data:**

***Food Security measurement***

We predict three measures of food security used by the international humanitarian organizations, including USAID and the World Food Programme (WFP): the reduced coping strategies index (rCSI), the household dietary diversity score (HDDS) and the food consumption score (FCS). The HDDS measures the number of different food categories that a household consumes in past seven days. The FCS gives nutrient related weighting to the count of food categories to come up with a weighted score of food quality. Higher values of both the FCS and the HDDS indicate higher food security and more diversity of nutrition intake. The rCSI reflects the number of coping strategies a household uses to address possible food shortages with higher values of rCSI indicating lower food security. The rCSI is believed to capture inadequate quantities of food consumed, which is consistent with acute food insecurity. Governments and international agencies apply cut-offs to categorize food security status rather than use the (Vaitla et al., 2017). This is why this paper focus on the categorical prediction for the given cutoffs instead of the continuous measures of food security in previous works (Lentz et al. (2019) and Jean et al., (2016), among others). The food security category is close to the actual policy scenarios where policymakers are trying to capture all the insecure households in a potential famine year in the currently used IPC system.

***Explanatory data***

The variables used to predict food security are high-frequency data, including precipitation, temperature, market prices, soil quality, and geographic variables. These data are generally collected remotely and are widely available. Variables regarding wealth status, asset ownership and household characteristics are created using answers from the LSMS surveys.

Household roof type is used as a crude proxy of poverty that can be accurately captured from satellite imagery. Cellular phones are access to financial resources, market information, and remittance flow (Eagle et al. 2010, Blumenstock et al. 2016) also serve as significant predictors.

1. **Method**

This section explains the main approach and techniques used in this paper. In summary, we use readily available data to model the food security status of village clusters in Uganda, Malawi, and Tanzania, with various machine learning related techniques.

***Categorical or continuous measure***

We focus on the categorical prediction for the given cutoffs of each food security measures as it is close to the actual policy scenarios where the policy makers need to locate places with most insecure households. We do care about the overall fit of the prediction on the actual food security measures and we achieve similar performance of model fit compared to previous studies at around 0.7 R squared. Since this paper focuses on successfully detecting the villages in need of food assistance, we use categorical measures of food security to transform the prediction into a classification problem. In this way, we can utilize data techniques such as choosing the right result metrics, sampling techniques to improve the chance of detecting insecure villages.

***Result metrics***

Predicting when and where the food security crisis will happen is more important than having an accurate assessment of the food security status of the general population. In technical terms, this study focuses on the recall rate of insecure households, rather than the overall prediction accuracy. Models aiming to maximize the overall accuracy tend to capture characteristics that are rich in the majority of the population and fails to understand the insecure households enough. We do want to maximize the recall rate to try and get all the insecure households, without a too low precision rate so that we do not mistakenly categorizing all the secure households as insecure. One of the population measures is the f-1 score serves as a balance between recall and precision, but in this particular application it does not put enough emphasis on the recall rate. Instead, we use a cost-sensitive learning approach to come up with our own f-1 score. The cost-sensitive learning approach penalizes misclassifications of the minority class more heavily by having a cost function, which is equal to the inverse of the class proportions. extra reward for identifying the minority class over the majority class, cost-sensitive learning changes this, and uses a function C(p, t) (usually represented as a matrix) that specifies the cost of misclassifying an instance of class t as class p. penalize misclassifications of the minority class more heavily than we do with misclassifications of the majority class, in hopes that this increases the true positive rate. In this paper, we have the cost equal to the inverse of the proportion of the different categories makes up. This increases the penalization as the class size decreases. The weighted f-1 score, the main result metrics that we use are calculated based on this function.

***Sampling***

Food secure households and villages make up the majority of the data samples. When we feed the prediction algorithms with the training data made up with this proportion, the models naturally pick up the characteristics of the secure households more than the insecure ones. As a result, the models tend to predict villages in the testing dataset to be secure. To force the models to gain as much information as possible regarding the imminent threat of food shortage, we applied the downsampling and oversampling techniques to force the model to learn about the tail of the distribution. These methods are broadly used to imbalanced datasets like the one we have about food security status. We use SMOTE to creates synthetic new data of the minority class by forming convex combinations of neighboring points, as a way to reduce the overfitting in oversampling.

***Data split***

In the case of spatial and temporal correlations among data, splitting the data set into training and testing is harder than one would think, as the assumption of independence between the training and the testing set is not easily satisfied. The classical assumption of a random split in generating the testing data set may not hold since the points randomly assigned to the testing may have strong spatial and temporal correlations with some of the points in the training set. Consequently, because

e use three different training, and testing data split methods to feature various applications. Yearly split is using one year as a training set to forecast places where the famine may happen in the future. The regional division is used to predict rural or more remote areas given current information in more accessible regions. Random split is used as a demonstration of general prediction or the “best guess” on unknown households based on all the information that we have.

***Data Segmentation***

For data segmentation, we compare the results of models trained on the entire dataset of three countries, with models trained by each country separately and then weight the recall rate by the number of households in each country. Similarly, we split the data even further by separate models trained on each region of the nations. Lastly, we train a shallow tree in each country based on observables to automatically split the data into several subsets.

By country

Entire dataset of three countries

By urban and rural

4. Auto-segmentation by training a shallow tree in each country based on observables

***Classification Algorithms***

Classification Tree (baseline and base learner)

Random Forest ( parallel )

Extreme Gradient boosting (sequential)

Xgboost performs better in capturing the minority classes than random forest, especially with oversampling techniquesTo reduce the overfitting problem involved with the large of variables we have in the model, we also tried ensemble learning such as random forest and XGboost. The ensemble learning methods improve model performances by averaging and sequentially improving the base trees.

For structured data like ours (unlike text or pure image), tree-based methods are popular.

Tree-based: Classification Tree (baseline and base learner), Random Forest, Extreme Gradient boosting

Boosting (Freund and Schapire 1997) is very similar to bagging but trees are grown sequen- tially. Each tree that can uses information from the previously grown trees. In boosting we don’t use bootstrapping, but fit the tree on a modified version of the original data set. In this ensemble technique, errors are corrected by sequentially adding new models to the existing models until no more improvements can be made. Boosting algorithms include some parameters which slow down the learning process. This slow learning process gives us better predictions (James et al. 2013). Another method related to boosting is the gradient boosting which was developed in several papers such as Breiman (1996); Friedman, Hastie, and Tibshirani (2000); Friedman (2001). In this method, new models are created to pre- dict the errors of the previous models. The gradient descent algorithm is used to optimize an arbitrary differentiable loss function while adding new models, it can be thought as a combination of gradient descent and boosting

Extreme Gradient Boosting (xgboost), developed by Chen and Guestrin (2016), is an efficient, flexible and portable variant of the gradient boosting model of Friedman, Hastie, and Tibshirani (2000) and Friedman (2001). Xgboost has been a winning tool for several Machine learning competitions (Adam-Bourdarios et al. 2015; Chen and Guestrin 2016). Xgboost relies on the same principles with gradient boosting but compared to gradient boosting, it is more efficient and faster since it uses sparsity aware algorithms and better processor utilization.

We also tried out algorithms of anomaly detection such as clustering methods, One-class SVMs, and Isolation Forests

***Baseline Model***

Classification Tree

Hyperparameters (e.g. max\_depth, max\_features) automatically selected by training data

Data split: year split

Data segmentation: by country

Down/over sampling: None

Variable groups:

1. Mkt: food price, market thinness
2. Asset: cellphone ownership, floor/roof material, asset index
3. Weather: dry spells, average temperature and rain
4. Location: elevation, distance to road, urban/rural
5. **Results**

***Parameter tuning and feature importance analysis***

For result measurement, we use the recall rate of the insecure category as the primary measure to evaluate the success of the models. Among models with similar recall-rate, we also compare other metrics, including AUC and precision, to find the best model.

Table 1: Baseline vs ML algorithms (year split) : Higher accuracy, similar recall

1. **Discussion**

***Error analysis***

of the primary model by region, by group, by month: presented in table and map.

Model generalization issues: what happens when we directly apply models trained in one country to predict another.

***Model deploy and update***

compare the results of using one year, with a dynamic process of continually updating the model with new survey data

The models are trained using a training set in one year. The accuracy of the models is evaluated using out-of-sample data in another year.

Our model tries to explain these variations in food security by the spatial-temporal variation in food availability and food access. Specifically, we align weather data with the crop growing season to describe the temporary shocks in food availability. We also align households with their most relevant market price, as shocks to income and household consumption budget.

To deal with the high dimensionality and nonlinearity problem, we apply machine learning methods including regularization methods (LASSO, Elastic net) and Ensemble learning models (Random Forest and Gradient boosting) to improve prediction accuracy. Another issue with the prediction accuracy is that the model works well on the quality measures of food security (FCS and HDDS), but a lot worse on the quantitative measure (rCSI). Partially due to the survey questions to the construction of the variable, the distribution of the rCSI appears to be highly skewed, a long-tail with a mass of points around zero. We employed oversampling and down sampling techniques to improve prediction performance.

The choice of the best model is the key in this paper. The criterion for choosing the best model is a fixture of prediction accuracy, recall rate (reducing type II error) and model interpretability.

Currently, the prediction accuracy in around an r squared of 0.6– 0.7 at the cluster level and around 0.4 at the household level. Preliminary results suggest assets related variables are explaining most of the variance in food security: cellphone ownership, asset index, and roof types. Market access variables, for example, distance to road and distance to markets are also important. Total rainfall, temperature and the start of the rainy season play a big role as well.

1. **Conclusion**

Combined with data techniques, machine learning methods not only improve prediction accuracy in general, but particularly on households that are vulnerable to food price shocks.

An automated, updated and scalable food security system based on publicly available data, advanced data techniques can assist the work of food aid and humanitarian responses in a timely, transparent, and efficient fashion

**Table 1: Baseline vs ML algorithms: year split**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Country | Food Security Measure | Overall  Accuracy  (baseline) | Overall  Accuracy  (ML) | Recall Rate Insecure category  (baseline) | Recall Rate Insecure category  (ML) |
| Malawi  2010/11, 2013 to predict 2015/16 | FCS | 0.70 | 0.69 | 0.04 / na | 0.00 / na |
| HDDS\* | 0.49 | 0.73 | 0.49 / na | 0.66 / na |
| rCSI | 0.39 | 0.69 | 0.23 / 0.00 | 0.79 / 0.00 |
| Tanzania  2010/11, 2012/13 to predict 2014/15 | FCS | 0.89 | 0.88 | 0.02 / 0.00 | 0.21 / 0.00 |
| HDDS\* | 0.79 | 0.80 | 0.99 / na | 0.95 / na |
| rCSI | 0.63 | 0.63 | 0.37 / 0.00 | 0.38/0.00 |
| Uganda  2010/11 to predict 2012 | FCS | 0.74 | 0.77 | 0.37/0.11 | 0.16 / 0.00 |
| HDDS\* | 0.88 | 0.88 | 1 / 0.00 | 1 / 0.00 |

**Table 2: Baseline vs ML algorithms with down/over sample technique**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Country | Food Security Measure | Recall Rate Insecure category  (Baseline) | Recall Rate Insecure category  ML + Oversample | Recall Rate Insecure category  ML + SMOTE | Recall Rate Insecure category  ML +   ADASYN |
| Malawi  2010/11, 2013 to predict 2015/16 | FCS | 0.04 / na | 0.93 / na | 0.10 /na | 0.16 /na |
| HDDS\* | 0.49 / na | 0.68 / na | 0.83 / na | 0.71 / na |
| rCSI | 0.23 / 0.00 | 0.80/ 0.00 | 0.16 / 0.00 | 0.13 / na |
| Tanzania  2010/11, 2012/13 to predict 2014/15 | FCS | 0.02 / 0.00 | 0.63/0.00 | 0.49/0.00 | 0.58/0.00 |
| HDDS\* | 0.99 / na | 0.66/na | 0.92/na | 0.85/na |
| rCSI | 0.37 / 0.00 | 0.44/ 0.00 | 0.42 / 0.00 | 0.46 / 0.00 |
| Uganda  2010/11 to predict 2012 | FCS | 0.37/0.11 | 0.24/ 0.00 | 0.44/0.33 | 0.43/0.33 |
| HDDS\* | 1 / 0.00 | 0.89/0.00 | 1 / 0.00 | 1 / 0.00 |

**Table 3: Data Split Comparisons**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Country | Food Security Measure | Year split | | Regional split | | Random split | |
|  |  | Accuracy | Recall | Accuracy | Recall | Accuracy | Recall |
| Malawi | FCS | 0.80 | 0.93 / na | 0.79 | 0.59 / 0.00 | 0.94 | 0.93 / 0.00 |
| HDDS\* | 0.68 | 0.68 / na | 0.90 | 0.89 / na | 0.94 | 0.93/ 0.00 |
| rCSI | 0.71 | 0.80/ 0.00 | 0.80 | 0.64 / na | 0.93 | 0.83 / 0.00 |
| Tanzania | FCS | 0.80 | 0.93 / na | 0.79 | 0.59 / 0.00 | 0.94 | 0.93 / 0.00 |
| HDDS\* | 0.68 | 0.68 / na | 0.90 | 0.89 / na | 0.94 | 0.93/ 0.00 |
| rCSI | 0.71 | 0.80/ 0.00 | 0.80 | 0.64 / na | 0.93 | 0.83 / 0.00 |
| Uganda | FCS | 0.76 | 0.24 / 0.00 | 0.77 | 0.27 / 0.00 | 0.79 | 0.56 / 0.60 |
| HDDS\* | 0.69 | 0.89 / 0.00 | 0.51 | 0.49 / 0.00 | 0.75 | 0.77/ 0.00 |

**Table 4: Data Segmentation Comparisons (keep the same testing set)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Overall | Food Security Measure | By country  With oversample and ML | One dataset  With oversample and ML | Rural Clusters only  With oversample and ML |
| Malawi  predict 2015/16 | FCS | 0.93 / na | 0.00 / na | 0.01 / na |
| HDDS | 0.68 / na | 0.62 / na | 0.46 / na |
| rCSI | 0.80/ 0.00 | 0.08 / 0.00 | 0.53 / na |
| Tanzania  predict 2014/15 | FCS | 0.63/0.00 | 0.00 / 0.00 | 0.19 / 0.00 |
| HDDS | 0.66/na | 0.96 / na | 0.97 / na |
| rCSI | 0.44/ 0.00 | 0.08 / 0.00 | 0.86 / 0.00 |
| Uganda  predict 2012 | FCS | 0.24/ 0.00 | 0.00 / 0.00 | 0.16 / 0.00 |
| HDDS | 0.89/0.00 | 0.89/ 0.00 | 0.91 / 0.00 |

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**Fig. 1 Map of FCS**

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**Fig. 2 Top tree split**

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**References**

Babenko, Boris, et al. "Poverty Mapping Using Convolutional Neural Networks Trained on High and Medium Resolution Satellite Images, With an Application in Mexico." *arXiv preprint arXiv:1711.06323* (2017).

Barrett, Christopher B., and Derek Headey. "A proposal for measuring resilience in a risky world." (2014).

Beegle, Kathleen, et al. *Poverty in a rising Africa*. The World Bank, 2016.

Blumenstock, Joshua, Gabriel Cadamuro, and Robert On. "Predicting poverty and wealth from mobile phone metadata." *Science* 350.6264 (2015): 1073-1076.

Castelluccio, Marco, et al. "Land use classification in remote sensing images by convolutional neural networks." *arXiv preprint arXiv:1508.00092* (2015).

Chen, Derek. "Temporal Poverty Prediction using Satellite Imagery." (2017)

Chen, Xi, and William D. Nordhaus. "Using luminosity data as a proxy for economic statistics." *Proceedings of the National Academy of Sciences* 108.21 (2011): 8589-8594.

Dang, Hai-Anh, Dean Jolliffe, and Calogero Carletto. "Data gaps, data incomparability, and data imputation: a review of poverty measurement methods for data-scarce environments." (2017).

Donaldson, Dave, and Adam Storeygard. "The view from above: Applications of satellite data in economics." *Journal of Economic Perspectives* 30.4 (2016): 171-98.

Engstrom, Ryan, Jonathan Hersh, and David Newhouse. "Poverty from space: using high-resolution satellite imagery for estimating economic well-being." (2017).

Head, Andrew, et al. "Can Human Development be Measured with Satellite Imagery?" *Proceedings of the Ninth International Conference on Information and Communication Technologies and Development*. ACM, 2017.

Henderson, J. Vernon, Adam Storeygard, and David N. Weil. "Measuring economic growth from outer space." *American economic review* 102.2 (2012): 994-1028.

Jean, Neal, et al. "Combining satellite imagery and machine learning to predict poverty." *Science* 353.6301 (2016): 790-794.

Kussul, Nataliia, et al. "Deep learning classification of land cover and crop types using remote sensing data." *IEEE Geoscience and Remote Sensing Letters* 14.5 (2017): 778-782.

Pokhriyal, N., & Jacques, D. C. (2017). Combining disparate data sources for improved poverty prediction and mapping. *Proceedings of the National Academy of Sciences*, *114*(46), E9783-E9792.

Steele, Jessica E., et al. "Mapping poverty using mobile phone and satellite data." *Journal of The Royal Society Interface*14.127 (2017): 20160690.