**Title:**

**Crop Simulation Model, Remote Sensing, GIS and their integration for Yield Monitoring**

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**Abstract**

Numerous weather, soil, and management factors that differ greatly in area and time considerably affect crop growth and productivity. Farmers can establish site-specific crop management practises while also learning useful information about their fields and crops through yield monitoring. The reveling of regional and temporal variability in crop yields is one of the key advantages of the yield monitoring system. The yield maps that are the end result of monitoring have a significant influence on the decision-making process. Mechanistic crop growth simulation models are helpful for predicting agricultural yield because they define crop development processes and quantify the impact of weather, soil, and management factors on crop growth and yield. Getting the spatial information on model input parameters, however, is the main obstacle to their application at the regional level. Data from remote sensing (RS), collected repeatedly over agricultural land, is useful for identifying and mapping crops as well as gauging crop vigour. With the advancement of RS data and techniques, the original attempts that directly linked RS-derived vegetation indices (VI) to crop yield have been supplanted by methods involving recovered biophysical quantities from RS data. In order to model and track crop growth at the regional level with inputs from remote sensing, crop simulation models (CSM) that have been successful in field-scale applications are being modified in a GIS framework with RS data. As a result, assessments are vulnerable to local soil variability, seasonal weather conditions, and crop management techniques. The leaf area index (LAI), crop phenology, crop distribution, and crop environment can all be learned from the RS data. This data is integrated with CSM in a variety of methods, including direct variable forcing, parameter re-calibration, and the use of simulation-observation discrepancies in a variable for yield monitoring correction.

**Concept of yield monitoring**

For a rising population to have enough food, crop yield monitoring is crucial. A component of precision agriculture called yield monitoring aids in giving farmers the information they need to make informed decisions about their fields. Farmers can learn useful information about their fields and crops through yield monitoring while also establishing site-specific crop management practices. The identification of regional and temporal variability in crop yields is one of the key advantages of the yield monitoring system. The yield maps that are the end result of monitoring have a significant influence on the decision-making process. Therefore, timely and accurate yield monitoring and estimating at a regional level is crucial for maintaining national food security and promoting sustainable agricultural growth.

**Chronological advancements in yield monitoring**

Initially, to simulate crop growth dynamics including LAI, canopy cover (CC), and the total dry biomass, mathematical formula-defined crop models are employed, (Curry, 1971). These models provide yield estimations and indicators of crop growth status, driven by dynamical elements such as the environment, management, and soil conditions (Launay and Guerif, 2005). However, when crop growth models are applied in large agricultural regions, the estimation accuracy of crop yield may be hampered by uncertainty regarding the geographic distribution of crop attributes, initial conditions, soil parameters, and field management techniques (Hansen and Jones, 2000). By supplying more relevant information, which would enhance model calibration and parameterization and boost the simulation accuracy at a regional scale, this uncertainty of crop models was minimised. In order to improve yield predictions, new methodologies or procedures can be used to effectively and efficiently integrate observable data into crop models (Curnel *et al.,* 2011). The rapid development of remote sensing technology that has made it possible to acquire timely crop growth status information during the growing season at the regional to global scale (Jarlan *et al.,* 2008). By making more use of these in crop models, this uncertainty can be minimised. For example, LAI (Aasen *et al.,* 2015), the percentage of photosynthetically active absorption (FPAR) (Baret *et al*., 2007), chlorophyll content (Jin *et al*., 2012), evapotranspiration (Mutiga *et al*., 2010), and soil moisture have all been estimated using remote sensing at various geographical resolutions (Hasan *et al*., 2014). To estimate biophysical and biochemical parameters from vegetative indicators, numerous techniques have been developed (Huang *et al*., 2015). Recently, it has been thought that using remote sensing data in crop models is a good way to keep track on crop development and yield (Li *et al.,* 2014).

**Crop growth model for yield monitoring**

Crop simulation models (CSAs) mimic how changes in the growing environment affect plant growth and development on a daily basis. They are based on real plant processes. A CSA is a straightforward illustration of a crop that serves as an explanation. Phenology, photosynthesis, dry matter generation, and dry matter partitioning are the main processes that are modeled in simulation models intended for potential production. Modules for phyllochron, branching pattern, and probable flowers/grain filling sites are among those targeting crop-specific behavior. Models of soil water balance, crop uptake and transpiration, and nitrogen transformations in soil, uptake, and remobilization inside plants, respectively, are incorporated to model the reaction of crop to environments with limited access to food and water. Weed and pest impact models are being developed and included in the advanced generation of crop simulation models.

State, rate, and driving factors are the three categories of variables identified in dynamic crop simulation models. Quantities that can be measured at certain times include biomass, soil nitrogen content, plant water content, and soil water content are considered as state variables. Driving variables, also known as driving functions, describe how the environment affects the system at its limits. Their values need to be continuously tracked, for example, meteorological variables. Each state variable has a set of rate variables that describe the rate of change for each state at any given time as a result of particular activities. These variables depict the movement of biomass or material between state variables.

The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project produced the Decision Support System for Agrotechnology Transfer (DSSAT), a computer software programme that integrates 11 crop simulation models with a standardised input and output. It has been tested and used in a number of nations. In India, the use of the CERES-Wheat component of DSSAT for predicting regional wheat yields was shown (Nain *et al.,* 2004).

**Basic Steps in crop growth simulation modelling**

1. Define goals: Agriculture system
2. Define system and its boundaries: Crop model
3. Define key variables:
	* State variables
	* Rate variables
	* Driving variables
	* Auxiliary variables
4. Quantify relationships (Evaluation)
5. Calibration/verification
6. Validation
7. Sensitivity analysis
8. Use of model in decision support

**Remote sensing for yield monitoring**

Remote sensing (RS) is a technique of gathering information about the Earth's land and sea surfaces by employing photographs taken from above and electromagnetic radiation in one or more parts of the electromagnetic spectrum that is reflected or emitted from the Earth's surface, (Campbell, 2006). We remotely gather data using a variety of sensors that may be processed to learn more about the thing, places, or phenomena being studied. Data can be collected in a variety of ways, for as by changes in acoustic wave distributions, or electromagnetic energy distributions.

Optical remote sensing uses VIS, IR, and SWIR sensors to create images of the Earth's surface. At these visible and infrared wavelengths, different material reflects and absorbs radiation in different ways. Targets can thus be distinguished from one another based on the spectral reflectance characteristics visible in the remotely sensed photographs.

Table 1: Various categories of optical RS systems

|  |  |
| --- | --- |
| Imaging system | Example |
| Panchromatic imaging systems | IKONOS pan, SPOT HRV-Pan |
| Multispectral imaging systems | Landsat MSS, Landsat ETM, Spot HRV-XS, IKONOS-MS |
| Super spectral imaging systems | MODIS, MERIS |
| Hyperspectral imaging systems | Hyperion on EO1 satellite |

In contrast, RADAR sensors work in the electromagnetic spectrum's microwave region, which is outside of the visible and thermal infrared range. Synthetic Aperture Radar (SAR) sensors have grown in significance as a source of data for monitoring and managing natural resources and agriculture. For example, RISAT-1, RADARSAT, Sentinel uses microwave radiation. Signal penetration inside of vegetation and soil targets is improved while operating in the microwave region. The longer wavelengths of a radar imaging system, as opposed to optical sensors, are unaffected by cloud cover or haze, allowing data collecting irrespective of atmospheric conditions.

In order to identify and distinguish the majority of the main crop varieties and circumstances, optical RS has been employed to monitor the situation of global agricultural production. However, using this technology for crop monitoring in agricultural areas with regular cloud cover can be problematic. Radar RS data, on the other hand, are sensitive to vegetation biomass and structure, making these sensors a desirable choice for crop monitoring. Radar data and wavelengths in the visible and infrared light both offer complementing information about various target characteristics. Intense research efforts are being made to apply RS technology as a result of the synergy between data from optical and SAR sensors. When combined, optical and radar data offer an important source of information for agricultural applications.

**Types of crop yield prediction through remote sensing**

1. **Empirical models with remotely sensed input**
2. Vegetation index
3. Spectral profile of crop growth
4. **Assimilation of remotely sensed data in crop simulation model**
5. Biophysical parameter ( LAI, chlorophyll content, nitrogen content)
6. Agro-meteorological parameter ( Insolation, LST, Rainfall, AET/PET, Soil Moisture)

**1. Empirical models with remotely sensed input**

RS data collected repeatedly over agricultural land aid in crop identification, mapping, and crop vigour assessment. The presence and concentration of photosynthetic pigments had an impact on the reflectance between 350 and 700 nm. The chlorophyll absorption band caused the dips in reflectance at 450 and 680 nm. Because of internal reflection, which is controlled by the interior structure of leaves, it was discovered that the reflectance between 800 and 1300 nm was at its highest. Due to the water absorption band, dips in the plant reflectance curve were seen around 1300 and 1900 nm. In order to identify functional correlations between crop features and RS observations, vegetation indices (VIs), which are mathematical combinations of canopy reflectance primarily in the red, green, and infrared spectral bands, are used. NDVI is the widely used VI for the yield monitoring. According to research by Zhou *et al*. (2017), the normalized difference red edge (NDRE) at heading stage accounted for 88% variation in the wheat grain production. With the advancement of RS techniques, the initial efforts that directly connected RS-derived VIs to crop output have been replaced by methods incorporating recovered biophysical quantities from RS data. Biomass is a crucial indicator for yield monitoring since it can reveal plant growth status. LAI and above-ground biomass can be calculated from RS data using parametric empirical correlations between in situ observations of the aforementioned components and vegetation indices. According to The predictive capability of partial least squares regression (PLSR) for dry matter retrieval from hyperspectral (EnMAP), superspectral (Sentinel-2), and multispectral (Landsat 8, RapidEye) remote sensing was studied by Gerighausen *et al.* (2016).

**2. Integration of RS inputs in crop simulation models**

Richardson et al. (1982) first suggested the use of RS data to increase the precision of crop models. They suggested using spectrally calculated LAI as a direct input to the physiological crop model or as an independent check to the model's computation for the model's re-initialization. The fundamental benefit of employing remotely sensed data is that it allows for a measurement of the real state of the crop over a vast region using less labor- and resource-intensive techniques than in situ sampling. Crop models offer a continuous estimate of growth through time, whereas RS offers a multispectral evaluation of the current state of the crops in a specific area. There are different ways to incorporate remote sensing data into the models:

(a) Direct use of a driving variable estimated from RS

(b) Updating of a state variable derived from RS (‘forcing’ strategy);

(c) Re-initialization of the model

(d) Re-calibration of the model

(e) Re-parameterization using coupled crop simulation models and canopy radiation models

(f) Corrective method

**(a) Direct use of driving variable**

The driving variables of crop simulation models are weather inputs, which comprise daily observations of the maximum and lowest temperatures, solar radiation, relative humidity, and wind speed etc. An important disadvantage to using this strategy is the insufficient availability of RS-derived metrics caused by the cloud cover issue and inherent characteristics of sensors and platforms. In order to predict provincial millet yields halfway through the crop duration to within 15% of their ultimate values, Thornton et al. (1997) used METEOSAT-based decadal (10-day) rainfall using cold cloud duration as input to CERES-Millet.

**(b) Forcing strategy**

The forcing technique entails using remote sensing data to update at least one state variable in the model. The most often updated state variable is LAI. Figure 1 illustrates the idea of a straightforward crop simulation model and how it is modified for RS-derived LAI forcing. Maas (1988) said that the forcing might be carried out either on the daily LAI profile or just on the day of the RS observation.

**(c) Re-initialization strategy**

The re-initialization method makes use of the fact that state variable initial conditions have an impact on model performance. To lessen the discrepancy between a derived state variable or radiometric signal and its simulation, it entails adjusting the initial condition of the state variable. The starting value of LAI (L0) during emergence can be changed to reduce the error function between remotely observed LAI values and simulated LAI values throughout simulation. (Maas, 1988). Results from updating (forcing) were identical to those from re-initialization using one observation.

**(d) Re-calibration/re-parameterization strategy**

This method makes the assumption that the model is formally adequate but has to be re-calibrated. By lowering the error between the state variable calculated by RS and the model's simulation of it, this is achieved. This renders a method which is susceptible to mistakes made when obtaining state variables from RS data. The the choice of parameter to adjust and the quantity of observations used in analysis depend critically on the model structure. Maas (1988) used remotely sensed GLAI measurements to show how the maize model needed to be re-calibrated. With the increase in number of parameters, more reliable estimates of LAI and biomass at anthesis were found, according to a multi-dimensional error function reduction technique.

**(e) Re-parameterization**

Instead of obtaining canopy parameters from radiometric data, crop models can directly use it while being re-initialized and re-parameterized (Moulin *et al.,* 1998). To simulate the temporal behaviour of canopy surface reflectance, which can be compared to satellite-observed canopy reflectance, a radiative transfer reflectance model is coupled to a crop production model in this method.

**(f) Corrective approach**

A correlation is established between the inaccuracy in the ultimate yield and the error in some intermediate variable as assessed via RS measurement. In a situation where the final yield is unknown, this connection may be used. Sehgal et al. (2005) used this technique to produce wheat yield maps for farmer fields during rabi 1998-1999 in Alipur block (Delhi).

**GIS, remote sensing and crop simulation model for yield monitoring**

Geographic information system (GIS), a powerful set of tools, can be used to collect, save, access at any time, modify, and display geographical data from the real world for a variety of purposes. (Burrough and McDonnell, 1998). Digital geographic data, computer software, and computer hardware are the three main components of a GIS. On the other hand, RS data collected repeatedly over agricultural land aid in crop identification, mapping, and crop vigour assessment.

It is a well-established practice to employ GIS along with RS data for yield monitoring during all stages of the activity, including planning, analysis, and output. GIS is used during the planning phase to either (a) stratify or zone an area using one or more input layers (climate, soil, physiography, crop dominance, etc.), or (b) convert input data (weather, soil, and collateral data) that are available in different formats into a common format. GIS is primarily used in the analysis phase to perform operations on NDVI raster layers or compute VI profiles within predetermined administrative borders. GIS is also utilised in the final output phase to aggregate and show results for specific regions (such as administrative regions) and to produce map output products with the required data integration through overlays.

**Interfacing crop simulation models to GIS**

Crop simulation models, used with input data from a particular field or site, produce a point output. Geographically variable inputs (soil, weather, and crop management), when combined with a GIS, can be used to improve crop yields, these simulation models' range of applicability can be expanded to a larger scale. The main objective of integrating models and GIS is to carry out simultaneous spatial and temporal analysis because region-scale crop behaviour has a geographic component and simulation models produce a temporal output. Although GIS and modelling tools have been around for a while, integration and the conceptual framework have only recently received attention. In their evaluation of GIS and agronomic modelling, Hartkamp *et al*. (1999) recommended using the terms "interface" and "interfacing" as catchall terms for using GIS and modelling tools at the same time, and linking, combining, and integrating as appropriate language for the degree of interfacing.

**(a) Linking**: GIS is used in straightforward linkage schemes to geographically show model outcomes. Model output interpolation is a straightforward strategy. An advanced tactic is to create a database that contains the model's inputs and export the model's outputs to the same database using GIS tools (interpolation, overlay, slope, etc.). Grid cell or polygon identifiers in input and output files are used to transport data between the GIS and the model. These files are transferred in binary or ascii format (Figure 2a). Due to (a) dependence on GIS and model formats, (b) compatibility issues with operating systems, and (c) underutilization of GIS capabilities, such an approach is unable to fully leverage the potential of the system.

**(b) Combining:** Combining also entails showing model outputs and processing data on a GIS, nonetheless, the model is configured with GIS, and data are immediately exchanged. This is accomplished using the GIS package's macro language, interface programmes, and user callable procedure libraries (Figure 2b). This calls for more intricate data management and programming than just connecting. AEGIS (Agricultural and Environmental GIS) and ArcView are an example of how to combine.

**(c) Integrating:** Integrating refers to the process of integrating two systems. A model is either integrated into a GIS system or a GIS system is integrated into a modelling system. This enables automatic usage of statistical software and relational databases (Figure 2c). This calls for a great deal of skill, work, and knowledge of the two tools. The AEGIS, created by Calixte et al. in 1992, is a regional agricultural decision support system that employs the DSSAT capabilities of ARC/INFO GIS for regional planning and productivity analysis. AEGIS enables the user to choose different spatially distributed crop management practise combinations and assess the prospective crop yield.

**Yield monitoring scenario in India**

The outcome of agricultural production is quite uncertain. The risk associated with farm production is increased by hazards and unforeseen extreme weather events. Numerous dangers have a direct impact on the welfare and production choices of farmers. As an agrarian nation, 48.9% of Indians work in agriculture either directly or indirectly (Economic Survey 2014-15). In 2015, 12,602 people in the farming industry (8,007 farmers and cultivators and 4,595 agricultural workers) died by suicide, making up 9.4% of all suicide victims in the nation (1,33,623). (National Crime Records Bureau statistics, 2015). Numerous governmental and non-governmental organisations have been working to alleviate the financial loss that farmers have experienced as a result of these unforeseeable events. The Indian government's Pradhan Mantri Fasal Bima Yojana (PMFBY) programme is one of its initiatives. With the aim of protecting farmers against crop losses, this insurance programme was introduced in 2016. The programme was established to shield farmers from the production-related risks and to motivate them to increase their crop investments. In reality, though, insurance corporations profit more than farmers. This is primarily due to the approach taken to estimate yield and damage. In India, crop counts are calculated using enumeration, and crop yields are evaluated using a sample survey method called a crop cutting experiment (CCE). In the field, crop cutting is accomplished by establishing a designated area, harvesting the crop there, and then weighing the crop. 20% of districts are chosen annually to participate in these studies. Therefore, the spatial variation in yield caused by variations in the chemical and physical qualities of soil, which may be obvious within a field itself, would not be taken into consideration by this experiment. Additionally, there is no systematic mechanism of recording the outcomes of CCE studies. By calculating the spatiotemporal variation of yield and crop acreage, the proper operation of this method (PMFBY) may be guaranteed. Manually carrying out these stages is laborious and time-consuming, and it may cause settlements to be delayed. With the development of remote sensing, it is now much easier to monitor crop health, crop yield, and other factors such as loss and risk associated with agricultural production in close to real-time. The crop health and other variables causing the spatial variance in agricultural output can be monitored by Satyukt Analytics, a RS expert.



Figure 1. Changes in model parameters before and after forcing of LAI (Wlv, Wst and TAGP implies weight of leaves, stem and total above-ground production, respectively)

GIS

MODEL

User

Interface

File exchange

1. Combining

GIS

MODEL

User

Interface

User

Interface

File exchange

1. Linking

GIS

MODEL

Pre-

processing

Pre-

processing

User

Interface

1. Integrating

**Figure 2:** Organizational structure for (a) linking, (b) combining and (c) integrating GIS and crop models

**References:**

Aasen, H., Burkart, A., Bolten, A. and Bareth, G. (2015). Generating 3D hyperspectral information with lightweight UAV snapshot cameras for vegetation monitoring: From camera calibration to quality assurance. *ISPRS Journal of Photogrammetry and Remote Sensing* **108**, 245-259.

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., Berthelot, B., Niño, F., Weiss, M., Samain, O. and Roujean, J.L. (2007). LAI, fAPAR and fCover CYCLOPES global products derived from VEGETATION: Part 1: Principles of the algorithm. *Remote Sensing of Environment* **110**, 275-286.

Burrough, P.A. and McDonnell, R.A. (1998). Principles of geographic information systems. Oxford University Press, Oxford, UK, pp. 10-16.

Campbell J. B. (2006). Introduction to Remote Sensing, The Guilford Press, Fourth Edition, 1-39781-593-8 in the United States of America.

Curnel, Y., de Wit, A. J., Duveiller, G. and Defourny, P. (2011). Potential performances of remotely sensed LAI assimilation in WOFOST model based on an OSS Experiment. *Agricultural and Forest Meteorology* **151**, 1843-1855.

Curry, R. B. (1971). Dynamic simulation of plant growth—Part I. Development of a model. Transactions of the ASAE, **14**, 946-0949.

Delécolle, R., Maas, S. J., Guerif, M. and Baret, F. (1992). Remote sensing and crop production models: present trends. *ISPRS Journal of Photogrammetry and Remote Sensing* **47**, 145-161.

Gerighausen, H., Lilienthal, H., Jarmer, T. and Siegmann, B. (2016). Evaluation of leaf area index and dry matter predictions for crop growth modelling and yield estimation based on field reflectance measurements. *EARSeL eProceedings*, **14(S2)**, 71-90.

Hansen, J. W. and Jones, J. W. (2000). Scaling-up crop models for climate variability applications. *Agricultural Systems* **65**, 43-72.

Hartkamp, A. D., White, J. W. and Hoogenboom, G. (1999). Interfacing geographic information systems with agronomic modeling: a review. *Agronomy journal* **91**, 761-772.

Hasan, S., Montzka, C., Rüdiger, C., Ali, M., Bogena, H. R. and Vereecken, H. (2014). Soil moisture retrieval from airborne L-band passive microwave using high resolution multispectral data. *ISPRS journal of photogrammetry and remote sensing* **91**, 59-71.

Huang, J., Tian, L., Liang, S., Ma, H., Becker-Reshef, I., Huang, Y., Su, W., Zhang, X., Zhu, D. and Wu, W. (2015). Improving winter wheat yield estimation by assimilation of the leaf area index from Landsat TM and MODIS data into the WOFOST model. *Agricultural and Forest Meteorology* **204**, 106-121.

India (2015). Economic Survey – 2015. The Government of India, Ministry of Finance National Crime Reports Bureau, ADSI Report Annual – 2015 Government of India.

Jarlan, L., Mangiarotti, S., Mougin, E., Mazzega, P., Hiernaux, P. and Le Dantec, V. (2008). Assimilation of SPOT/VEGETATION NDVI data into a sahelian vegetation dynamics model. *Remote Sensing of Environment* **112**, 1381-1394.

Jin, X. L., Wang, K. R., Xiao, C. H., Diao, W. Y., Wang, F. Y., Chen, B. and Li, S. K. (2012). Comparison of two methods for estimation of leaf total chlorophyll content using remote sensing in wheat. *Field Crops Research* **135**, 24-29.

Jones, J.W. 1993. Decision support systems for agricultural development, pp. 459-471. In: Systems Approaches for Agricultural Development, Vol. 2. (Penning de Vries, F.W.T., Teng, P. and Metselaar, K. eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands.

Launay, M. and Guerif, M. (2005). Assimilating remote sensing data into a crop model to improve predictive performance for spatial applications. *Agriculture, Ecosystems & Environment* **111**, 321-339.

Li, Y., Zhou, Q., Zhou, J., Zhang, G., Chen, C. and Wang, J. (2014). Assimilating remote sensing information into a coupled hydrology-crop growth model to estimate regional maize yield in arid regions. *Ecological modelling* **291**, 15-27.

Maas, S. J. (1988). Use of remotely-sensed information in agricultural crop growth models. *Ecological modelling* **41**, 247-268.

Moulin, S., Bondeau, A. and Delecolle, R. (1998). Combining agricultural crop models and satellite observations: from field to regional scales. *International Journal of Remote Sensing* **19**, 1021-1036.

Mutiga, J. K., Su, Z. and Woldai, T. (2010). Using satellite remote sensing to assess evapotranspiration: case study of the upper Ewaso Ng’iro North Basin, Kenya. *International Journal of Applied Earth Observation and Geoinformation* **12**, S100-S108.

Nain, A. S., Dadhwal, V. K. and Singh, T. P. (2004). Use of CERES-Wheat model for wheat yield forecast in central Indo-Gangetic Plains of India. *The Journal of Agricultural Science* **142**, 59-70.

Richardson, A. J., Wiegand, C. L., Arkin, G. F., Nixon, P. R. and Gerbermann, A. H. (1982). Remotely-sensed spectral indicators of sorghum development and their use in growth modeling. *Agricultural Meteorology* **26**, 11-23.

Sehgal, V. K., Sastri, C. V. S., Kalra, N. and Dadhwal, V. K. (2005). Farm-level yield mapping for precision crop management by linking remote sensing inputs and a crop simulation model. *Journal of the Indian Society of Remote Sensing* **33**, 131-136.

Thornton, P. K., Bowen, W. T., Ravelo, A. C., Wilkens, P. W., Farmer, G., Brock, J. and Brink, J. E. (1997). Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology* **83**, 95-112.

Zhou, X., Zheng, H.B., Xu, X.Q., He, J.Y., Ge, X.K., Yao, X., Cheng, T., Zhu, Y., Cao, W.X. and Tian, Y.C. (2017). Predicting grain yield in rice using multi-temporal vegetation indices from UAV-based multispectral and digital imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* **130**, 246-255.