*Remote sensing for developing world agriculture: opportunities and areas for technical development*



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# Remote sensing for developing world agriculture: opportunities and areas for technical development

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## ABSTRACT

A parameterized numerical model is constructed to compare platform options for collecting aerial imagery to support agriculture electronic information services in developing countries like India. A sensitivity analysis shows that when Unmanned Aerial Vehicles, UAVs, are limited in flight altitude by regulations, the velocity and altitude available to manned aircraft lead to a lower cost of operation at altitudes greater than 2000ft above ground level, AGL. If, however, the UAVs are allowed to fly higher, they become cost-competitive once again at approximately 1000ft AGL or higher. Examination of assumptions in the model highlights two areas for additional technology development: baseline-dependent feature-based image registration to enable wider area coverage, and reflectance reconstruction for ratio-based agriculture indices.

**Keywords:** remote sensing, agriculture, aerial imagery, multispectral

## 1. INTRODUCTION

Driven by population growth, increases in per capita consumption and changes in diets, global food demand is expected to roughly double from 2005 to 2050.[1] India will experience a relatively larger proportion of this production pressure not only because of its expected growth rates in population and per capita income, but because it must support about 17% of the world population and 15% of its livestock on only 2.4% of the world's geographical area.[2] Indian farmers and researchers must find ways to significantly increase agricultural yield to meet these growing food demands.

Despite this, there is plenty of room for improvement in Indian agriculture. Many farms in industrialized countries are already approaching the theoretical maximum yield of the crops they grow.[3] Indian agriculture, however, lags behind, indicating a significant potential for increased yield through improved cropping practices and farm management. For example, China produced 94% more rice paddy per hectare than India in 2010. Bangladesh, Indonesia, and Vietnam also produce more than India by 24%, 48%, and 57%, respectively.[2] This indicates a significant potential for increased yield through improved cropping practices and farm management. Beyond improving farmers' own wellbeing and food security, improved agricultural yields and reduced risk in the agricultural sector can lead to increased investment and more food security for the country and region.

Precision agriculture (PA) is an approach to crop management built around measuring and responding to variation in plant and soil health to reduce spatial and temporal variations in crop yield. PA supports more targeted application of seeds, fertilizers and pesticides in order to avoid excessive runoff, maximize utilization efficiency, respond to in-season disturbances like pests and diseases, and reduce farmers' costs. In industrialized countries, PA involves the application of technology to detect crop health and vary inputs, but in any location it relies on up-to-date information about crop status and best practices.[4]

Traditionally, government-funded agriculture extension services provided the link between farmers and this up-to-date information. Unfortunately, despite renewed interest and investment from government extension programs, the extension efforts of the national agricultural research system, cooperatives, and nongovernmental organizations, the coverage of agriculture extension services in India is inadequate.[5] The National Sample Survey Office estimates that only 41% of farmers accessed technical advice during the sample period from 2012 to 2013, and the most-consulted resources were a progressive farmer in their community and radio/tv/newspaper/internet.[6]

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Newer information technology-based extension services, dubbed eExtension services, are in development in India and around the world. Whether based on farmer call centers, text messages, smartphones, or connected field agents, these eExtension systems offer the ability to provide personalized, plot-specific information to farmers, and to respond directly to the problems they face in their fields. In order to personalize the recommendations from these systems, however, information on crop status must somehow reach the eExtension services. Remote sensing offers an efficient way to collect this monitoring information and allow the production of plot-specific data for Indian farmers.

Remote sensing in India, however, requires a different approach to that used so far in industrialized countries. As described here, the economics, spatial properties, and heterogeneity of farming in India lead to a need for wide-area mid-resolution sensing. This paper outlines the motivation for and structure of a remote sensing system suited to densely populated smallholder crop farming areas in developing countries such as India, and identifies areas for technical research needed to make it possible and practical. Data for this paper was derived from four visits to India over two years, and included conversations with and observations of stakeholders in six Indian states, from farmers to input suppliers, academic agriculture researchers to hired labor. Observations were compiled and combined with literature reviews to determine a list of salient features of Indian smallholder agriculture, which are then used to develop design parameters of a data collection system to support small farmers.

Properly supporting Indian farmers with predictions of droughts and pests, actionable insights, and effective responses based on the latest agriculture science can not only help some of the world's most vulnerable populations earn more and improve their livelihoods, but it can also reduce risk across an industry, opening investment opportunities and promoting economic growth and resilience.

## 2. FUNDAMENTALS OF REMOTE SENSING IN AGRICULTURE

Remote sensing is the utilization of sensor technology to detect relevant properties of a subject from afar. In the case of crop agriculture, that subject is a field of plants during the growing season, and the sensor is an optical camera. The camera is carried on a platform, most often a ground vehicle, UAV, manned aircraft, or satellite. The platform determines how far away from the subject the camera is during operation and, combined with the camera parameters, how much crop area can be sensed in each produced image. A platform which operates further from the subject (e.g., higher off the ground) allows a wider field of view in the camera at the expense of image detail. Ground sampling distance (GSD) is the distance between the centers of two image pixels on the ground, and determines the minimum size of feature that can be resolved in the image.

Since the 1970s, researchers have been aware that plants reflect sunlight differently at different wavelengths in the electromagnetic spectrum. In particular, wavelengths in the near infrared spectrum (800-1000nm) are reflected significantly more than wavelengths in the visible spectrum (400-800nm). Early experiments with satellite imagery led to the development of the Normalized Difference Vegetation Index (NDVI) as a way to measure plant vitality from remotely sensed reflectance images taken via satellite.[7] Multispectral cameras are designed to capture multiple images of the same scene, each one showing the intensity of reflected light in a specific waveband. These wavebands are applied in some algebraic combination to create vegetation indices like NDVI, which represent a particular crop property.

## 3. REMOTE SENSING CHALLENGES IN INDIA

Providing farmers in India with remote sensing data in a useful form is challenging. The structure of Indian agriculture makes implementing remote sensing technologies developed for farming in highly industrialized nations impractical and cost prohibitive. These challenges include:

*Plot size:* Average size of landholding in India is 1.16 hectares (2.87 acres), but this does not tell the whole story.[8] The average landholding value is falling, and has reduced in size every time data was taken since the beginning of the Indian Agriculture Census (1970).[8] In addition, landholdings are often divided into even smaller plots for reasons of land profile (e.g., terraces), soil suitability, or inheritance practices. This leads to actual plot sizes as small as 200$m^2$ or smaller. Finally, different plots owned by the same farmer are rarely adjacent to each other, and are often separated by considerable distances (see Figure 1).


Figure 1. Aerial imagery from Google Maps shows farmland in West Bengal, India. On the left, orange bars indicate lengths of 20m, showing field sizes of less than 200m$^2$ (0.02ha). On the right, a single farmer's landholding is highlighted in white. The three fields are separated by approximately 800m.

*Field variability:* Because adjacent plots are often owned by different farmers, they are also planted at different times and with different crops. This makes it more difficult for a crop-specific pest or disease to move across a landscape. However, smaller plots make infestation of a farmer's entire field occur faster and allows less time to take countermeasures. This means that a pest or disease can infect an entire plot much faster, and the robustness to disturbances is generally lower than for a larger field. Thus disturbances must be detected more quickly in order to be useful to farmers. Coupled with the proportion of a typical farmer's income represented by each plot, the speed of disease spreading suggests a high update frequency is critical for any type of disturbance detection method for Indian smallholder farmers.

Field variability also points to a wide-area coordinated approach to remote sensing for smallholder farmers. By the nature of the varied crops and planting times in adjacent fields, diseases may have to "jump" across larger distances to infest the next field of its chosen crop. A coordinated wider view of more fields would allow advance notice to be given to famers whose plots are within a susceptible distance of currently-infected fields. This would allow for preventive measures to be taken, reducing risk of excessive losses.

*Capital spending:* Even though agriculture in India contributes 14% to the country's GDP of 1.9 trillion USD, and 11% of its exports, on the individual farm scale, the amount of money available for investment is too small for a farmer to purchase and operate his or her own remote sensing system.[2] Farmers earn an average of only 6,426 INR (108 USD) per month and, after consumptive expenses, retain only 513 INR (8.61 USD) per month for net investment in productive assets.[6] This suggests that some form of collective method of financing, whether based in a public organization or private business, would be most suited to collecting, processing, and interpreting remote sensing data, and serving it to individual farmers.

*Information needs:* Indian farmers require a different approach to remote sensing than farmers of larger fields in industrialized countries. Precision agriculture, as it is implemented on farms in industrialized countries, utilizes yield monitors, variable rate technologies, and remote sensing to allow a farmer to divide his or her large field into smaller management zones, and vary crop treatments over that large field.[9] These techniques are used to optimize yield after the best advice for scouting, seeding, and planting have already been implemented. In contrast, Indian farm fields are often smaller than the management zones used by industrialized farms, and so require a different approach to optimizing their yields.

Indian farmers face a significant lack of reliable information and decision support in their day-to-day operations. The Ministry of Agriculture operates a farmer extension service, but its own report in 2012/2013 describes challenges including "understaffed extension," "insufficient planning at district level and below," and "lack of support to knowledge intensive alternatives for rain-fed farming."[2] Both literature and field research found that the government extension service is widely regarded as unable to fulfill its mandate.[10] Other sources of information for farmers include direct contact with one of the state agriculture universities, which can only serve a tiny fraction of farmers; family or locally-shared techniques, which are not up-to-date without a connection to extension or research; and from input (pesticide or fertilizer) suppliers, who may have some training, but also have a conflict of interest in what advice to supply and products to recommend.

Small-plot farmers would be well-served by a single aggregate sensing of their field, rather than a high-resolution sensing method which divides their small plot into even smaller management zones. Unlike large industrialized farms that require remote sensing for the farmer to observe in-field variation, small plots can be easily inspected by the farmer on foot. Thus, farmers are often already intimately familiar with which parts of their field underperform due to, for example, poor soil type or water drainage issues. While this variation could eventually be useful to detect from a remote sensing platform, the benefit of sub-plot resolution imagery is less clear than the first step of providing plot-specific sensing results.

*Education levels:* Farmer education levels in India are low, shown by the 2011 census' results of a 74% overall literacy rate (likely much lower among farmers).[11] While local experience is invaluable for farming, lack of education can prevent effective interpretation and application of remote sensing data. For this reason, any system which proposes to collect imagery for use by farmers must also include significant analysis and interpretation components. This paper considers primarily the technical aspects of data collection, however, the analysis and interpretation steps are just as important in the implementation of a remote sensing system to benefit smallholder farmers.

*Multi-season planting:* The climate in much of India allows two growing seasons per year: Kharif (July-October) and Rabi (October-March). Particularly in areas in which irrigation water is accessible, two or even three different crops will be grown on the same plot of land in a single year. Because of the range of crops planted both on a single plot, and variation in crops in adjacent plots, the flexibility to modify detected wavebands and integrate new research in crops' spectroscopic responses is important to offering the best data interpretations to farmers.

*Airspace restriction:* Many government aviation bodies were caught off-guard by the rapid proliferation of low-cost commercially available UAVs in the past few years, and are still working to safely integrate their use into existing air traffic control laws and regulations. In India, the response of the Directorate General for Civil Aviation was to disallow any civilian use of UAVs while new guidelines were created.[12] At the time of this writing, a set of draft guidelines is being circulated for feedback which limits UAV flights to 500m from and in visual line-of-sight of the operator, which would severely limit a wide-area coverage mission.[13]

## 4. DESIGN REQUIREMENTS

The above observations lead to a set of design requirements which differ from those of existing remote sensing systems. The properties outlined in Table 1 describe the conditions which must be met in order for the collected data to be applicable in the context of small Indian farms. These conditions will inform the design of a remote sensing system to serve these users.

Table 1. Design parameters uncovered during user research of Indian smallholder farmers. Each value is described as a limit, to indicate the minimum performance necessary.

| **Property** | **Value** |
|---|---|
| Image resolution (GSD) | 8m (maximum) |
| Return time | 2x per week (minimum) |
| Sensitivity | Capable of identifying crop stress (minimum) |
| Level of interpretation | Actionable recommendations (minimum) |

*Image resolution:* In order to serve Indian small-plot farmers, the ground footprint of each detected pixel must be entirely contained in a single field. This means that the pixels must be no larger than the smallest field, however there is no requirement for the pixel to be any smaller than the smallest field, as long as enough pixels can be accurately placed entirely within each field to be surveyed. If the smallest field is ~10m on a side, this gives a maximum pixel dimension of 8m (with a 1m buffer on each side).

*Return time:* As described above, a short return time is necessary to identify and alert the farmer to disturbances in their field before an entire plot is negatively impacted. This value can vary depending on the crop, types of disturbances, and sensitivity of the sensors.

*Sensitivity:* Remote sensing information, however it is collected, must be useful to farmers. The first step in this is the ability to tell farmers that their crops are stressed before the farmers are capable of noticing the problem themselves. Other benefits of remote sensing are possible, such as vegetation vigor, yield prediction, etc. described by Atzberger, but this is the minimum for a system to be considered "useful."

*Level of interpretation:* Small farmer education levels and experience with mapping techniques suggest that analysis and interpretation is required for most farmers to take advantage of remote sensing data.

Once the above criteria are met, the priority for a remote sensing system for Indian farmers is the lowest possible cost. The requirement of low cost and its corollary of collective sensing described above suggest that area coverage should be maximized. The next section examines the parameters of aerial sensing platforms and compares off-the-shelf technology to meet these requirements.

## 5. SYSTEM MODEL

To find the lowest-cost data collection system which meets the requirements as outlined in section 2, a model is sought which relates the requirements to parameters of the hardware and operations needed to meet them. To first estimation, the goal is the relatively straightforward task of flying a camera over the target area and taking pictures. An analytical model is proposed to provide insight into the most important parameters, and then a numerical simulation is described which provides additional detail.

### 5.1 Analytical model

To first order, the area covered by an aerial platform in a single day, $A_{day}$, is equal to the product of the range, R, it can fly in a day and the swath width of the camera it carries. This swath width depends upon α, the included angle of the sensor and lens system, and AGL, the height above ground level at which the platform flies. Assuming a human operator is directly involved in operations, the total duration of daily flights can be assumed to be constant ($t_{day}$). Thus the area covered during a day is described as:

$$A_{day} \propto (v_{cruise} * t_{day}) * AGL * \tan \alpha.$$

Where $v_{cruise}$ is the cruise velocity of the platform. This holds true as long as the pixel size on the ground remains smaller than the maximum allowed pixel size, $px_{max}$:

$$px_{max} > \frac{2 * AGL \tan\left(\frac{\alpha}{2}\right)}{res_x}$$

where $res_x$ is the transverse resolution of the sensor in pixels.

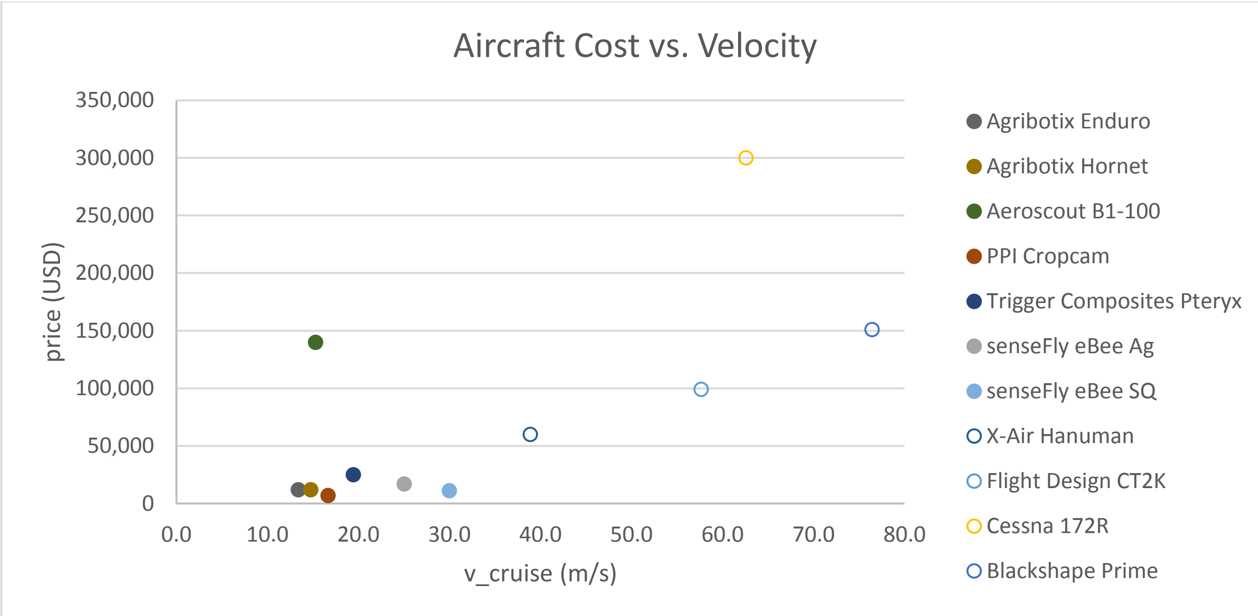


Figure 2. A comparison of purchase price to cruise velocity of civilian UAVs and light manned aircraft. Filled markers represent UAVs, open markers show manned aircraft, and platforms are listed on the right in order of increasing v_cruise. Data collected from Jane's All the World's Aircraft and manufacturers' and retailers' websites.[14]

The cost of the platform varies widely between different options currently in production. The cost to collect data is composed of the capital costs, $C_{cap}$, (e.g. the platform and the camera) and the operational costs, $C_{opp}$ (e.g. primarily operator and fuel). Some correlation was found between velocity and purchase price (see Figure 2) for small UAVs and small manned aircraft.

The total cost of the platform, $C_{day}$, is

$$C_{day} \propto \frac{C_{cap} + C_{opp}}{v_{cruise} \times AGL \times \tan \alpha} \quad (1)$$

By the inverse relationship to $v_{cruise}$, AGL, and α, Eq. 1 shows that even a slight increase in any of these variables can lead to a significant reduction in the overall cost, depending on the multipliers in the proportion. To determine the sensitivity of these variables, a numerical simulation was constructed and tested with reasonable values from currently available products and wages.

### 5.2 Numerical model

A numerical simulation was built in MATLAB to compare different platform parameters. The goal was to identify a configuration which allows the lowest cost data collection over a large contiguous area, while maintaining the minimum design parameters outlined in section 2. It was found that the significant velocity, range, and altitude advantage offered by small manned aircraft outweigh the extra costs in their operation for this particular situation.

Table 2. Parameters and symbols used to estimate cost and performance of different platform and camera configurations.

| Symbol | Units | Parameter |
|---|---|---|
| Platform parameters | | |
| R_mi | miles | range on a single charge or tank |
| v_pf | m/s | cruising speed |
| AGL_max | m | maximum operating height above ground level |
| g_turn | g | maximum wing loading in a turn |

| | | |
|---|---|---|
| t_gnd | hr | time between consecutive flights (for refueling, data download, etc.) |
| N_pf | # | number of platforms in simultaneous operation by a single operator |
| C_pf | USD | capital cost of one platform |
| LT_pf | days | expected lifetime of platform |
| C_oper | USD/yr | cost of pilot or operator |
| C_fuel | USD/gal | cost of fuel (electricity is treated as free) |
| fuel_rate | gal/hr | Rate of fuel use under normal flight |
| C_transport | USD | cost of transport vehicle |
| LT_transport | days | lifetime of transport vehicle |
| v_transport | mph | average velocity of platform transport (e.g., a van to carry UAVs) |
| Camera parameters | | |
| res_h | pixels | image resolution in the horizontal (transverse) direction |
| res_v | pixels | image resolution in the vertical (longitudinal) direction |
| α | degrees | Included angle of lens system |
| C_camera | USD | purchase price of camera |
| LT_camera | days | expected lifetime of camera |
| FR | frames/sec | frame rate of camera |
| Mission parameters | | |
| px_max | m | maximum allowable pixel size on the ground |
| OL_s | % | proportion of images to overlap in the transverse direction |
| t_day | hr | maximum mission time in one day |
| D_yr | days | operating days in one year |
| f_flights | #/week | number of flights over the same area per week |
| L_season | days | length of a growing season |

Profiles were assembled of typical UAV parameters (based on the senseFly eBee Ag) and manned aircraft (based on the Cessna 172R), and then varied to judge sensitivity of the relative parameters. For any particular AGL value, the optimum α is that which provides a pixel size of just at or below px_max. If α is too large, however, then lens distortion makes image correction difficult. For the purpose of this work, α was limited to 110 degrees, which produces a 7m wide pixel at approximately 10,000ft AGL when res_h = 1280 pixels.

To estimate the area surveyed in a single flight, the width of the field of view of the camera on the ground is calculated based on AGL:

$$FOV_w = 2 * AGL * \tan\left(\frac{\alpha}{2}\right)$$

Before beginning a survey (or landing), the platform must climb to its assigned AGL or descend to its landing point. The range of the platform, R, is divided into three parts:

$$R = R_{climb} + R_{survey} + R_{descend}$$

$R_{climb}$ and $R_{descend}$ are assumed to be equal for simplicity. They are calculated using the platform's rate of climb parameter (ROC):

$$R_{climb} = \frac{AGL}{ROC} * v_{pf}$$

$R_{survey}$ can then be used to calculate the survey area. A square lawnmower pattern is assumed, and the distance flown in a 180° turn at the end of each row, $d_{turn}$, is calculated based on the time required to make the turn (see Figure 3). A standard rate turn is defined by the US Federal Aviation Administration as 3° per second, or one minute to turn 180°, so $t_{turn}$ = 60 s is used for all manned aircraft.[15] Smaller UAVs can turn much faster, so video footage is used to estimate a 5-second 180° turn for any UAVs in the simulation.

$$d_{turn} = t_{turn} * v_{pf}$$

The lawnmower pattern is taken to be square, so the length and width of coverage area, $A_L$ and $A_W$, must be equal. Each row in the pattern requires a flight of distance $A_L$+$d_{turn}$, thus the survey flight distance, equal to the range of the platform, is

$$R_{survey} = N_{rows} * (A_L + d_{turn})$$

Solving for $A_L$ gives

$$A_L = \frac{R_{survey}}{N_{rows}} - d_{turn}.$$

The width of the coverage area, $A_W$, is equal to $N_{rows}$ multiplied by the width of each row. In order to effectively process the images, a side overlap, $OL_s$,is required. The side overlap is chosen as 30% for the purposes of the simulation, and is maintained constant for all platforms.

$$A_W = N_{rows} * FOV_w * (1 - OL_s)$$

Setting $A_L$ = $A_W$ and solving for the platform range, R, produces a second order quadratic in $N_{rows}$:

$$R_{survey} = FOV_w * (1 - OL_s){N_{rows}}^2 + d_{turn}N_{rows}$$

Using the quadratic equation, $N_{rows}$ is shown to be equal to

$$N_{rows} = \frac{-d_{turn} + \sqrt{{d_{turn}}^2 - 4 * FOV_w(1 - OL_s) * -R_{survey}}}{2 * FOV_w(1 - OL_s)}$$

With $N_{rows}$ known, the flight survey area can be calculated as the product of the area's length and width:

$$A_{flight} = A_L * A_W$$

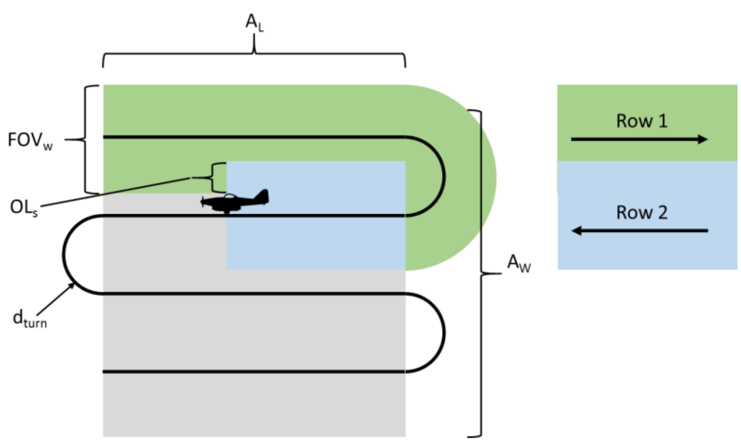


Figure 3: Sketch of a simple lawnmower pattern shows turn distance, field of view, and side overlap.

If multiple platforms are flown by a single operator, then the mission area, $A_{mission}$, is the flight survey area times the number of platforms in the mission:

$$A_{mission} = A_{flight} * N_{platforms}$$

For each platform, a parameter of $t_{gnd}$ indicates the time needed on the ground between missions to refuel, download data if necessary, and relaunch. This is particularly relevant for UAVs, which have short flight durations, but can be recharged/refueled quickly and fly multiple flights in a day. In this case, it is assumed that a truck would be used to transport one or more UAVs a distance of $A_L$ between consecutive flights. This vehicle's average speed, $v_{transport}$, is given as a parameter in the model, and the mission time is calculated as

$$t_{mission} = t_{flight} + t_{gnd} * N_{pf} + \frac{A_L}{v_{transport}}.$$

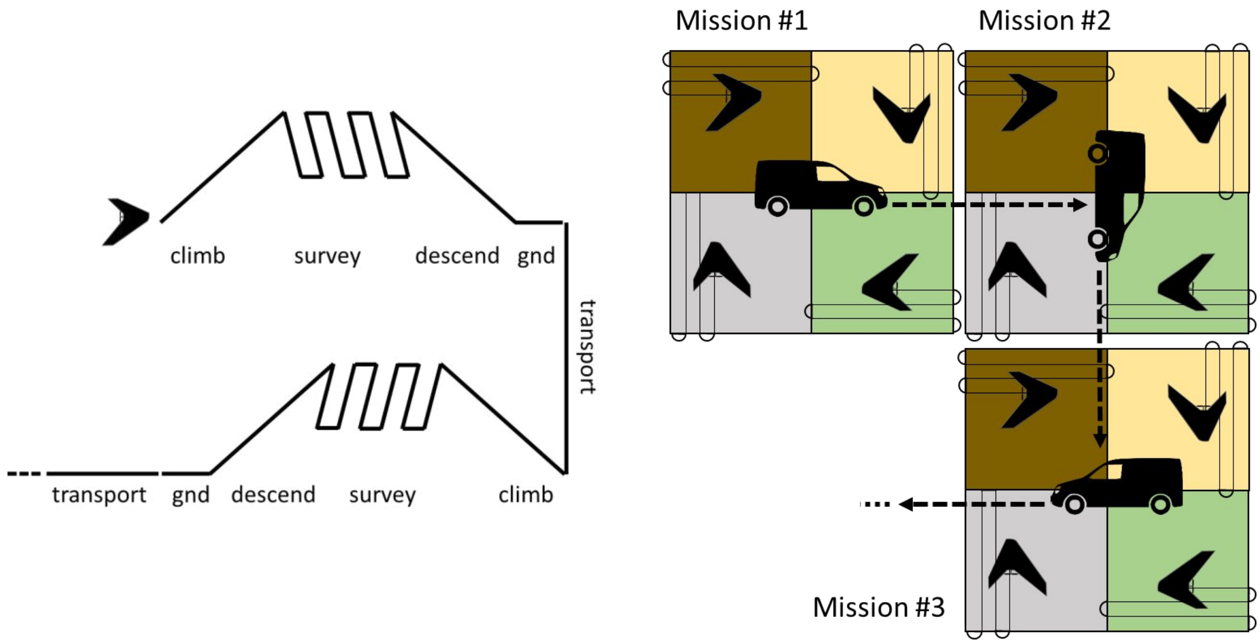


Figure 4: Sketch descriptions of UAV survey operations. On the left, a single UAV goes through five steps for each flight. On the right, four UAVs each perform one flight over adjacent areas, making up one mission. They are then transported by van to the next survey area, and so forth.

The area covered in a single day of operations, $A_{day}$, is

$$A_{day} = A_{mission} * \frac{t_{day}}{t_{mission}},$$

where $t_{day}$ is the duration of a workday with usable sunlight. $t_{day}$ was chosen as 10 hours for this simulation.

Cost of use is divided between capital costs, $C_{cap}$, and operational costs, $C_{op}$. $C_{cap}$ is amortized over the lifetime of each component, estimated yearly operational costs are divided by the number of operational days in a year ($D_{yr}$):

$$C_{cap} = \frac{C_{pf}}{LT_{pf}} * N_{pf} + \frac{C_{camera}}{LT_{camera}} * N_{pf} + \frac{C_{transport}}{LT_{transport}}$$

$$C_{op} = \frac{C_{operator}}{D_{yr}} + \frac{C_{maintenance}}{D_{yr}} * N_{pf} + C_{fuel} * t_{day} * fuel_{rate} * N_{pf}$$

Cost of fuel for electric UAVs is assumed to be zero, and cost of fuel for manned aircraft, $C_{fuel}$, is given in gallons per hour. The total cost of operations for one day is the sum of the capital and operational costs:

$$C_{day} = C_{cap} + C_{op}$$

Commercial surveying using UAVs as a publically available service is only just becoming a reality, so reference values were not available at the time of writing. For the Cessna 172R, the values used in the simulation (listed in appendix) produced cost per hour of flying of \$220, which is consistent with rates for passenger flights in the Boston area.

## 6. RESULTS

As expected, larger AGLs lead to higher area coverage and lower cost per area. When UAVs are limited in AGL by regulations (such as the US FAA's operating ceiling of 400ft), the velocity and AGL available to manned aircraft lead to a lower cost of operation above an operating AGL of 2000ft. If, however, the UAVs are allowed to fly higher, they become cost-competitive again (see Figure 5). The additional complexity of a single operator transporting, maintaining, and flying multiple UAVs must also be taken into account when considering this option.

It is clear that regulation plays a large role in determining whether a particular remote sensing approach is the most cost-effective. The established procedures surrounding manned aircraft operation make them less expensive at the current time, but this may change with the introduction and development of new guidelines for UAV operation both in India and in other countries.

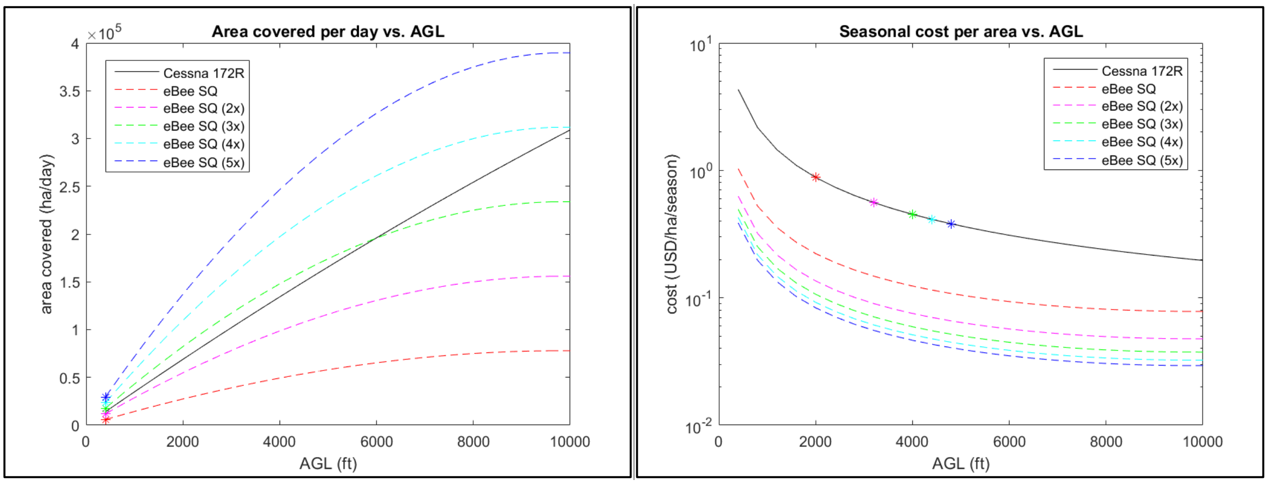


Figure 5. Simulation results show the area covered per day and seasonal cost per area vs. AGL. On the left, it is clear that multiple UAVs have the potential to cover more area than a manned aircraft for a given AGL. Unfortunately, current regulations constrain UAVs to only the left-most altitude (starred). On the right, the current UAV operating points (400ft AGL) are indicated as stars on the line for the Cessna 172R. For example, a Cessna would have to fly at 2000ft AGL to be cost-competitive with a single eBee SQ.

## 7. DISCUSSION

The results above show how close UAVs and manned aircraft are in their operational costs and performance, when the goal is wide-area survey coverage. As regulations change, civilian UAVs are allowed to fly higher, and they are able to fly faster and farther, the cost of aerial data collection will fall significantly.

The above analysis relies on two assumptions which are necessary for the projected aerial survey costs to be achieved. These assumptions present areas for future research and development in the processing of aerial images.

First, the ability to fly such that a camera's pixel size on the ground is nearly as large as the size of the fields being surveyed presents challenges in image registration and geolocation. Subpixel accuracy is necessary in order to ensure that the sensed pixels are entirely contained within field boundaries. In this particular application, however, we have the luxury of surveying the same areas over and over again. This fact allows the image processing algorithm developer to take advantage of (a) higher-resolution imagery collected only once per season and (b) a priori knowledge of the shape and relative locations of image features. Thus, more accurate image registration can be achieved, ultimately increasing the size of $px_{max}$ and reducing the cost of repeat data collection.

Second, we assume that the sensors in use are capable of detecting true crop reflectance, despite changes in incident light, AGL, atmospheric effects, and image processing techniques. Because the calculated vegetation indices rely on ratios of detected crop reflectance values, a clear understanding of the accuracy of these values is critical. This is an active area of research for all forms of remote sensing.[16] Methods are under development which are particularly suited to wide-area aerial remote sensing, in order to allow reflectance data to be more closely compared between surveys on different days.

## 8. CONCLUSION

The benefits of remote sensing have so far been under-realized in developing world agriculture. The Mahalanobis National Crop Forecast Centre, a government program to use remote sensing, has been effective in helping government agencies manage food market prices from a macro view, but the coarse (250m to 1km resolution) data has been of little direct use to farmers.[17] This paper describes an application of user centered design to identify the necessary parameters for a remote sensing system to produce data of use to Indian smallholder farmers. Observations from two years of field visits are described, and from them the essential components of a functional remote sensing system are distilled.

A theoretical model is described to evaluate the trade-offs between different available remote sensing platforms, and a simulation shows that manned aircraft are the most cost-effective option under current regulatory conditions. Future work is described in order to meet two assumptions made in the theoretical model: baseline-dependent feature-based image registration to allow greater area coverage and lower data collection cost, and reflectance reconstruction for ratio-based agriculture indices to ensure maximum sensitivity to changes in crop status. These areas of research are applicable regardless of the platform carrying the data collection system.

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## APPENDIX

Model parameters for base cases (modifications as listed in text).

| Symbol | Units | senseFly eBee SQ UAV | Cessna 172R |
|---|---|---|---|
| Platform parameters | | | |
| R_mi | miles | 62 | 635 |
| v_pf | mph | 68 | 140 |
| AGL_max | ft | 400 | 5,000 |
| ROC | ft/min | 690 | 645 |
| g_turn | g | 1.5 | 0.35 |
| t_gnd | hr | 0.25 | 1 |
| V_transport | mph | 40 | n/a |
| N_pf | none | 4 | 1 |
| C_pf | USD | 11,000 | 300,000 |
| LT_pf | days | 1000 | 2000 |
| C_oper | USD/yr | 30,000 | 100,000 |
| C_fuel | USD/gal | 0 | 100,000 |
| fuel_rate | gal/hr | 0 | 10 |
| C_transport | USD | 30,000 | 0 |
| LT_transport | days | 3000 | n/a |

Two cameras were used in the model. The Parrot Sequoia is a recently released off-the-shelf camera containing four low-resolution multispectral imagers and one high-resolution RGB imager. The High Speed Multispectral Multi-Camera Array was constructed as part of this research, and contains seven high-speed multispectral imagers.

| Symbol | Units | Parrot Sequoia | HSMMCA |
|---|---|---|---|
| Camera parameters | | | |
| res_h | pixels | 960 | 960 |
| res_v | pixels | 1280 | 1280 |
| α | degrees | 70.6 | 42 |
| C_camera | USD | 4000 | 6000 |
| LT_camera | days | 600 | 600 |
| FR | frames/sec | 1 | 10 |

Mission related parameters reflect agricultural limits, image processing, and operational decisions.

| Symbol | Units | |
|---|---|---|
| Mission parameters | | |
| px_max | m | 7 |
| OL_s | % | 60 |
| t_day | hr | 10 |
| D_yr | days | 200 |
| f_flights | #/week | 2 |
| L_season | days | 100 |
| C_fuel | USD/gal | 10 |