Towards improving opium yield estimates using remote sensing

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Yearly estimates of illicit opium production are key metrics for assessing the effectiveness of counter narcotics policy in Afghanistan. Poor security often prevents access to sample locations and puts pressure on field surveyors, resulting in biased sampling and errors in data recording. Supportive methods using aerial digital photography for improving yield estimates were investigated in the UK in 2004, 2005 and 2010. There were good empirical relationships between NDVI and poppy yield indicators (mature capsule volume and dry capsule yield) for individual fields. The results suggested a good generalised relationship across all sampled fields and years (R^2>0.70) during the 3–4 week period including poppy flowering. Regression estimates using this relationship with the imagery counteracted bias in the sample estimate of yield, reduced sample error and enabled the production of detailed maps showing the poppy yield distribution. The application of this approach using VHR satellite imagery was investigated in the context of the annual opium survey in Afghanistan. Initial results indicated the potential for bias correction of yield estimates using a smaller and targeted collection of ground observations as an alternative to random sampling.

1 Introduction

Annual estimates of illicit opium production in Afghanistan are produced by the United Nations Office on Drugs and Crime/Afghanistan Ministry of Counter Narcotics (UNODC/MCN) from the estimated cultivated area of opium poppy (*Papaver somniferum*) multiplied by the average yield per unit area of dry opium gum calculated from field survey. Even in relatively safe areas, local survey teams can be subjected to coercion or corruption and access to some of the sample locations may be impossible, especially as the key poppy growing provinces in the south are the least secure. These security constraints reduce the quality of the data and compromise the random design of the survey.

In response to questions on the veracity of the yield survey data raised by stakeholders, the UNODC/MCN developed statistical tests to assess the quality of their data (UNODC, 2012). They determined that data from surveyors correctly following the protocol would capture a wide variation in poppy capsule volumes. Field data were considered unreliable if the coefficient of variation of capsule volume was below a threshold or if the capsule measurements contained duplicates. Data failing the tests were removed and in 2012 revised estimates for the period 2006–2009 were published. Only a small number of the total surveyed fields were considered suitable for inclusion in the revised estimates (table 1). For 2009, the estimate is made using observations from only 16 fields (<8 ha) out of a total of 123,000 ha of poppy cultivation in Afghanistan and reduces the overall estimate of opium production by 36%.

Changes since 2012 in the training and supervision of surveyors and the selection of survey sites in safer working areas, have resulted in improved field data quality according to the UNDOC's test criteria. However, these changes reduce the number of surveyed fields – from 685 in 2011 to 114 fields in 2012 – and result in a non-random sample design that produces a statistically un-representative estimate of opium yield in Afghanistan (UNODC, 2012). This estimate will bias the average dry opium yield and hence the yearly estimate of opium production.

Table 1: Revised opium yield estimates 2006-2009 after UNODC quality testing (UNODC, 2012)

year	surveyed fields	fields passing all tests	original yield, kg ha^{-1}	revised yield estimate, kg ha^{-1}	% reduction in production estimate
2006	714	153	37.0	32.3	13
2007	531	76	42.5	38.5	6
2008	568	71	48.8	37.8	22
2009	699	16	56.1	32.2	36

2 Background

2.1 *Opium yield estimate in Afghanistan*

Objective estimates of average yields in national crop surveys, for example in the US, are typically made by cutting and weighing from a random sample of small plots. Early yield forecasts are sometimes made from the same plots by measuring yield indicators such as plant stand density, and number and size of fruiting heads (Vogal and Bange, 1999).

In Afghanistan opium gum is harvested by hand by a process known as lancing. The mature green capsules are scored using a wooden tool with five or six small blades mounted in a row at one end. With a single stroke, multiple parallel incisions are made to the capsule surface, typically in a diagonal orientation. The opium gum 'bleeds' from the incision and is scraped from the capsule surface the following day. This process is repeated 3–7 times on new sections of the capsule surface. The fresh opium gum has variable moisture content and is dried to create a more standardised and concentrated product. Estimation of dry opium yield using direct measurements of opium gum is impractical for field survey because of the protracted multiple lancing and gum collection and the need for drying.

The UNODC/MCN make opium yield estimates indirectly using sample measurements of the volume of capsules per unit area and an empirical relationship to dry opium gum yield based on data collected in Pakistan and Thailand (UNDCP, 2001):

$$Y = \frac{(V_c + 1495) - ((V_c + 1495)^2 - 395.259V_c)^{0.5}}{1.795} \tag{1}$$

where Y is dry opium gum yield (kg ha^{-1}) and V_c is mature capsule volume (cm^3 m^{-2}).The volume of an individual capsule (V_{ci}) is calculated using the prolate spheroid model:

$$V_{ci} = \frac{4}{3}\pi ab^2 \tag{2}$$

where a is half the capsule height excluding the stigma and b is half the capsule diameter. The same authors also present an empirical equation using the weight of capsules per unit area instead of volume:

$$Y = \frac{(W + 184) - ((W + 184)^2 - 493.92W)^{0.5}}{2.94} \tag{3}$$

where W is mature capsule dry mass (kg ha^{-1}). The capsule volume approach is used by UNODC in Afghanistan, as it is quicker and avoids the need to remove capsules for weighing.

Measurements are taken at sample locations selected randomly from a sample frame of village locations across the poppy producing provinces. At each selected village, a surveyor subjectively chooses three fields that represent good, normal and poor crops. Within each field, three 1 m^2 quadrats are positioned randomly along a transect, explained UNDCP (2001). In each quadrat, the number of capsules, flowers and buds expected to contribute to yield are counted and the average volume per capsule estimated by measuring a subsample comprising all capsules on randomly selected plants until at least 10 capsules have been measured. These measurements are used to estimate the total volume of capsules per unit area and equation 1 is applied to estimate the dry opium yield for each quadrat. An average yield (weighted by province area) is then calculated and multiplied with the cultivated area of opium poppy to estimate the dry opium production. This methodology is very time consuming and a large number of samples are required to make credible estimates of opium yield at regional and national level.

2.2 *Remote sensing of yield*

Remote sensing methods have been used to assist in the estimation of crop yield by exploiting relationships between measured crop parameters and spectral properties. Linear combinations of red (R) and near-infrared (NIR) reflectance, referred to as vegetation indices (VIs), are correlated to measured crop parameters such as leaf area index, above ground biomass and plant stand density, which in turn are correlated to final yield in crops of wheat, millet, soybean, cotton, barley, tomato and maize in a range of geographical locations (Tucker *et al.*, 1980; Rasmussen, 1997; Liu and Kogan, 2002; Domenikiotis *et al.*, 2004; Weissteiner and Kühbauch, 2005; Koller and Upadhyaya, 2005; Prasad *et al.*, 2006).

Taylor *et al.* (1997b) exploited the relationship between VIs and above ground biomass in cereal crops by extrapolating yield indicator measurements across aerial digital photography (ADP) to minimise the requirement for field observations. They modelled Normalised Difference Vegetation Index (NDVI) and yield estimates based on samples of plant population, number of viable tillers, number of ears per unit area and number of viable grains per ear at different crop growth stages. They found that the spatial pattern of crop development and yield potential in fields and field groups is established early in the crop cycle, indicating a relatively wide window of opportunity for acquisition of imagery to support yield estimation.

This methodology was developed further in the context of precision farming of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) by Wood *et al.* (2003). Only eight sites were required to correlate NDVI and yield indicators for a group of similar fields, provided the selection of sites was constrained to represent the range of NDVI across the fields and samples had good geographic distribution and separation.

These studies are based on a statistical technique known as the regression estimator (Cochran, 1977), where the correlation between high accuracy sample observations and coarser data representing the population (known as an auxiliary or co-variate) are used to reduce the variance of the sample estimate. This technique has been tested operationally at the regional scale using imagery for improving crop inventories in Europe by the Monitoring Agriculture with Remote Sensing (MARS) programme (Taylor *et al.*, 1997a) and by the USDA in the United States (Allen and Hanuscak, 1988). The population mean for individual crops was calculated from digital image classification and substituted into the linear regression of the sample observations with the coincident pixels from the digital classification. These programmes found a reduction in variance of the sample estimate and a correction for highly biased samples using imagery.

A regression based approach could provide improved precision in sample estimates from the small yield sample in Afghanistan and correct for the bias in the sample distribution if a correlation between opium yield indicators and VIs was established. Suitable very high resolution (VHR) satellite imagery is already collected by the UNODC/MCN at random locations as part of their annual opium cultivation survey. If the yield ground survey took place at these locations the VHR imagery could provide a basis for improved yield estimation.

In this paper we present research into improving yield estimation in Afghanistan with remote sensing. Firstly the relationship between poppy yield indicators and NDVI is investigated at field sites in the UK. The application of a regression estimator utilising satellite imagery collected for the UNODC/MCN's cultivation survey in Afghanistan is then discussed. The field trials were originally conducted for the UK government as part of wider project, described by Taylor *et al.* (2010), to investigate the uncertainty in Afghan opium production estimates. Further work was conducted of behalf of the UNODC/ MCN using data from their 2011 and 2012 yield surveys and VHR imagery collections.

3 UK field trials

3.1 *Field sites*

Controlled field experiments involving opium poppy are not possible in Afghanistan as cultivation is illegal. Instead, initial field experiments were conducted in the south of England in 2004 and 2005 on opium poppy grown for the pharmaceutical industry. The fields were located within a few kilometres of each other on the same farm in Hampshire. In 2004 the field names and areas were: 'No 34' (24.8 ha) and 'Aero4' (22.9 ha). In 2005 they were 'L21' (7.62 ha) and '25–6–7' (32.45 ha). The planting dates for opium poppy in 2004 were 8 March in Aero4 and 23 April in No34, which had been replanted later because of frost damage. In 2005 both L21 and 25–6–7 were planted on 15 March. Parts of the fields L21 and 25–6–7 that were used for other experimental trials are excluded from analysis in this study. In 2010 a further two poppy fields (4.36 and 18.68 ha) near Haseley, Warwickshire where added to the trial. In all cases the fields were managed using standard agricultural practices, with uniform inputs of fertiliser and pesticide within each field.

3.2 *Crop growth stages and timing of aerial digital photography*

The NDVI response of crops varies with time because of the change in R and NIR spectral response through the growth stages of the crop. Poppy growth stages have not been formally defined so the following description was developed in consultation with agronomists in charge of the commercial crop.

The growth and development of the poppy crop starts with the emergence of cotyledons followed by progressive leaf production, which is often referred to as cabbage stage because of the resemblance to early growth of cabbages. Stem elongation follows which sees the emergence of downward-pointing buds forming characteristic 'hooks' at the top of the stems. As the stem lengthens the hook straightens and the bud develops into the flower. Individual flowers last about 24 hrs and are followed by development and swelling of the green capsule which can last up to two weeks as the seeds develop. Additional capsules are often produced on secondary stems emanating from the main stem in a progression so flowering of the crop as a whole can last several weeks with 'hooks', flowers and capsules being present at the same time. It is during this period that opium gum would be harvested in Afghanistan by lancing. The capsules then mature and dry, and the leaves drop as the plant senesces. Planting density is variable and complete canopy

Table 2: Planting dates, image acquisition dates and poppy crop growth stages at each field site.

field site	planting date	image date	growth stage
Aero4	8-Mar-04	11-Jun-04	Flower bud development/flowering
		28-Jun-04	Capsule development
		13-Jul-04	Seed development
		6-Aug-04	Senescence
No34	27-Apr-04	11-Jun-04	Leaf production/stem extension
		28-Jun-04	Flowering
		13-Jul-04	Senescence
		6-Aug-04	Seed development
L21 & 25-6-7	15-Mar-05	12-May-05	Leaf production
		7-Jun-05	Stem extension/bud development
		22-Jun-05	Flowering/capsule development
		12-Jul-05	Seed development/senescence
Haseley	15-Mar-10[a]	24-Jun-10	Capsule development

[a] Approximate date.

closure does not usually occur, especially in Afghanistan where farmers need to walk through the crop at harvest.

Ground observations of the poppy crop and field reports were used to plan the timing of image acquisition but this was not an exact process because of flying constraints imposed by weather conditions and logistics. Imagery acquisitions were achieved for the growth stages shown in table 2. There were visible differences in crop morphology at the imagery acquisition dates in 2004 resulting from the seven week delayed planting date and the increased planting density of field No34 compared with Aero4. Poppy plants in field No34 had single, smaller capsules and were shorter in height. The timing of progression through growth stages was accelerated, with the poppy in No34 moving through leaf production, stem extension to flowering, faster than Aero4. The capsules in No34 had less time to grow and develop, as both fields reached senescence around the same date.

3.3 *Processing of aerial digital photography*

Near vertical aerial photography was acquired with digital cameras mounted in the fuselage of a light aircraft. The ADP system was the same as used by Taylor *et al.* (1997b) and Wood *et al.* (2003) and comprised of two Kodak DCS 420 digital cameras, fitted with optical band-pass filters used to simultaneously acquire images in the red (R, 640 nm centre, 10.4 nm band width at half maximum transmission) and near infrared (NIR, 840 nm centre, 11.7 nm width) wavebands. The above ground flying heights of 1200 m (4000 ft) and 500 m (1650 ft) were used to achieve ground pixel resolutions of 0.6 m and 0.25 m, respectively. The cameras were set manually to the same exposure (f-stop and shutter speed) and ISO settings to achieve the correct relative magnitudes of the red and near infrared but the settings were adjusted according to flying height and ambient light. The shutter speed was fixed according to flying height, 1/125 for 1200 m and 1/250 for 500 m, to control motion blur. The raw digital numbers (DNs) of each pixel were recorded onto removable storage inside each camera.

The ADP imagery collected from the R-NIR camera pair were co-registered and geometrically corrected to the UK Ordnance Survey of Great Britain (OSGB) map coordinate system to within 1 m accuracy. A grey and white reference panel (1.6 m by 1.6 m) were used to radiometrically normalise the DN values between dates. The NDVI was calculated from the normalised DN values using the equation:

$$\text{NDVI} = \frac{N - R}{N + R} \tag{4}$$

where N is the near infrared and R is the red response of the camera. A low pass filter was applied to each image (7x7 and 5x5 kernels used with 0.25 m and 0.6 m resolution respectively) to reduce small-scale variations in NDVI and differences in colocation between image pixels and ground measurements (Wood *et al.*, 2003).

Examples of two-band false colour composites (FCC) of Aero4 and No34 with NIR in red and R in blue and green, acquired on 11 June 2004 are shown in figure 1 along with the respective NDVI images. Both FCC images show areas to be in cloud shadow which could not be avoided at the time. Closer visual inspection of NDVI values in and out of shadow in uniform crop areas showed that the NDVI calculation greatly reduced cloud shadow effects (figure 1) to the point where they could be ignored. The other image dates were not affected by cloud.

3.4 *Selection of ground calibration sites*

The rapid calibration methodology proposed by Wood et al. 2003 was implemented to select eight sites representing the range of NDVI within the field. To achieve this, the NDVI values were stratified into eight equal ranges and a site was randomly selected from within each stratum. Figure 2 shows an example of the stratification of NDVI applied to No34 and the location of the calibration sites. The same procedure was used to select calibration sites in Aero4. In 2005 eight calibration sites were selected across the two fields, to calibrate a total of 40 ha. One additional calibration site was added using a later NDVI image, to provide extra data representing low to average biomass poppy. In 2010 six calibration sites were selected in each of the Haseley fields.

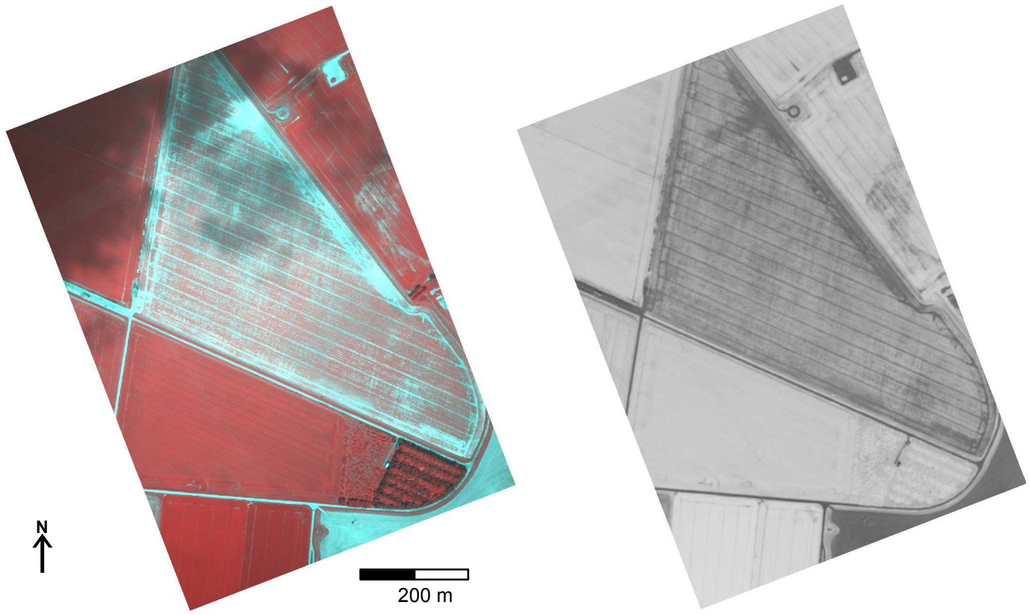
3.5 *Crop measurements*

Crop measurements were made on the same dates as image acquisition in three 1 m^2 quadrats at each calibration site, positioned in a triangle formation as shown in figure 3(a) and orientated so that the diagonal was aligned with the direction of planting to avoid aliasing with plant rows. Spatial averaging of the triplets was used to match the field observations to the imagery resolution and reduce any error in co-location.

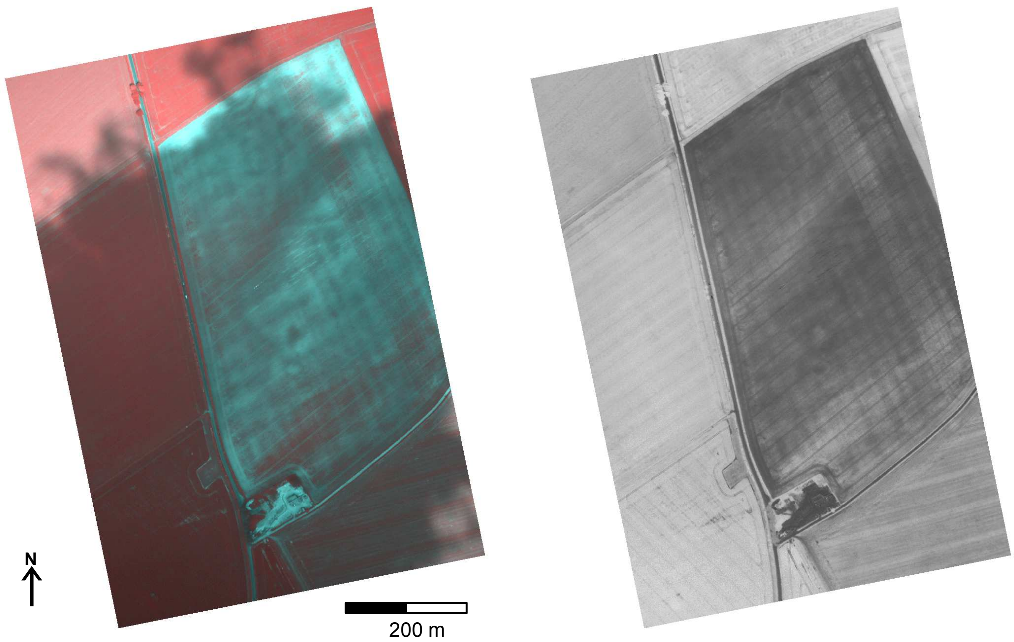
Depending on the growth stage, the measurements made were: plant stand density, weed counts, bud and capsule counts, and capsule dimensions. Capsule height was measured between the stigmatic rays to the base of the ovary (figure 3(b)). On the final date the capsules were harvested from each of the 1 m^2 quadrats and oven dried for 3 days at 75 °C, to determine the dry capsule yield.

A digital photo of each sub-sample at each date was taken from a vertical height of approximately 3 m using a compact digital camera mounted on a wooden pole (figure 3(c)). These images were rectified and provided a visual record of the individual quadrats (figure 3(d)).

Timing within the crop growth cycle was established by visually estimating the predominant growth stage and assigning a numerical value based on the scale given in table 3. Typically plants in a poppy crop have a mixture of stages such as flower buds, flowers and capsules occurring at the same time. If there was no clear majority growth stage, an intermediate numerical value was assigned. For example, between leaf production and stem extension, the value 1.5 was used.



(a)



(b)

Figure 1: Presence of cloud shadow in original false colour composite ADP (left) and after calculation of NDVI (right) for (a) Aero4 and (b) No34. Imagery collected 11 June 2004 in Hampshire, UK.

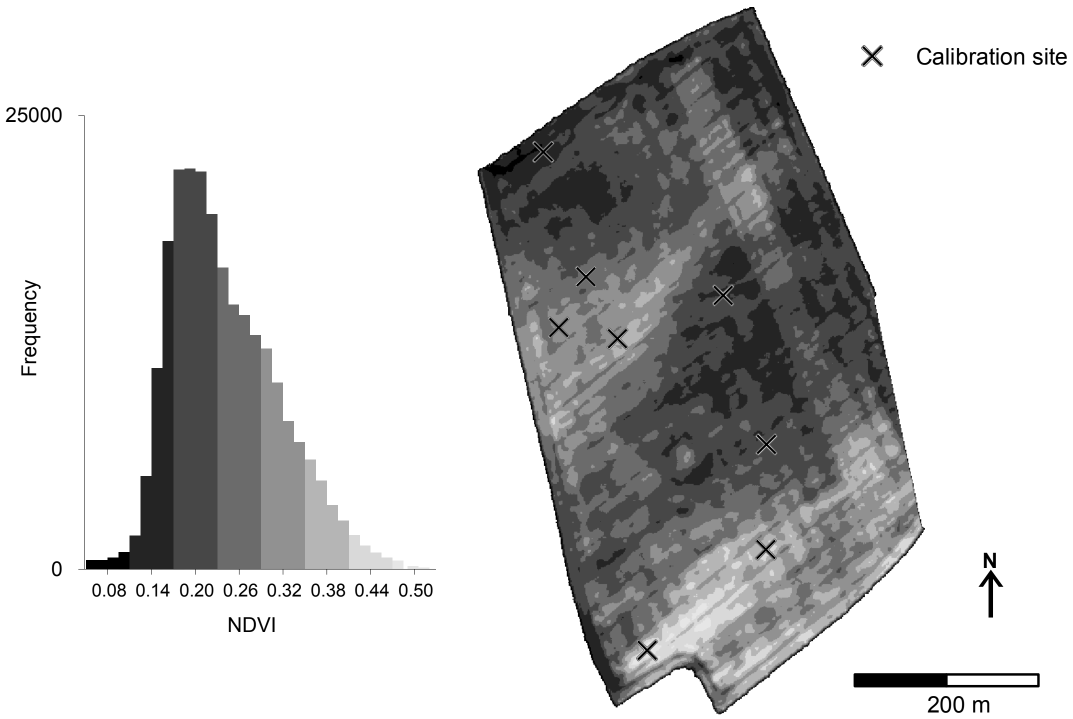


Figure 2: Stratification of field No34 into eigth classes based on equal intervals of the NDVI image histogram. The location of selected calibration sites within each strata are marked. Image aquired on 11 June 2004.

Table 3: Summary of the poppy growth stages in sequential order.

poppy growth stage	date sequence
Emergence (cotyledons)	0
Leaf production (cabbage stage)	1
Stem extension	2
Flower bud development (hook stage)	3
Flowering	4
Capsule development	5
Seed development	6
Senescence	7

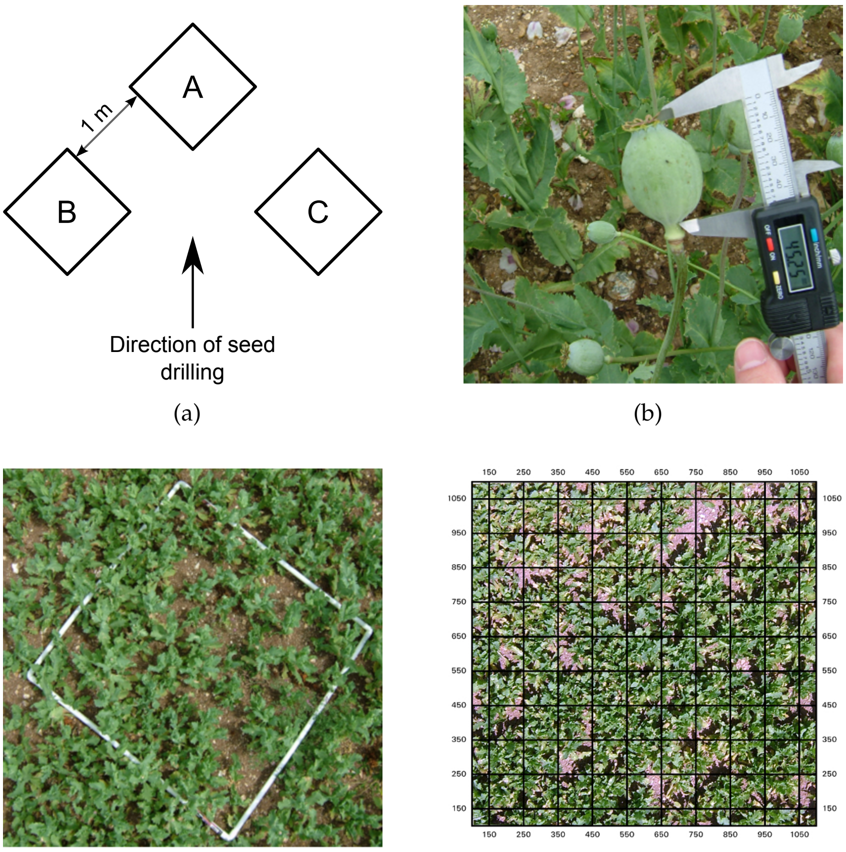
3.6 *Crop yield indicators and NDVI*

The empirical relationship between measured crop parameters and NDVI was determined using linear regression as follows:

$$y = a(\mathrm{NDVI}) + b \tag{5}$$

where y is the crop parameter to be estimated, NDVI is the normalised difference vegetation index (equation 4), a is the slope and b is the offset. The regression parameters were applied to the NDVI values in the whole image to estimate a chosen crop parameter for any image pixel. Maps showing the within-field variation of the crop parameter can then be produced.

Figure 4(a) shows the coefficient of determination (R^2) between NDVI and mature green capsule volume at different crop growth stages, using equation 5. The highest correlations occurred during the 3–4 week period around flowering. The equivalent relationship between NDVI and final dry capsule yield is shown in figure 4(b) with R^2>0.9



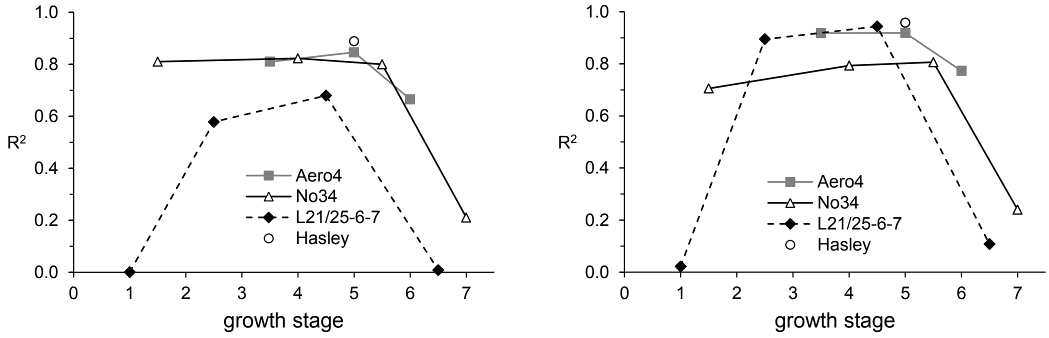
(a) (b) (c) (d)

Figure 3: Field measurements: (a) Orientation of 1 m^2 quadrats in sample triplet; (b) height of capsule measured with callipers between stigmatic rays and base of ovary; (c) near vertical ground photograph of quadrat; and (d) rectified near vertical ground photograph.

during flowering to capsule development for Aero4 and L21/25–6–7, and R^2=0.793 and 0.806 at flowering and seed development respectively in No34.

The correlations are better for dry capsule yield than mature capsule volume for most of the growth stages. This is attributed to the total dry mass of the harvested capsules within each quadrat containing less measurement error compared to the subsample of capsule volume measured in the field. The timing of capsule measurements also effects the accuracy of the estimate of mature capsule volume as there may be capsules at different stages of maturity within any single quadrat that make identifying the optimum time for survey subjective.

In figure 5 data from the three study sites are shown grouped by growth stage: (a) leaf production to stem extension, (b) flowering and (c) capsule development to seed development. NDVI data was plotted against mature capsule volume (left) and dry capsule yield (right). The NDVI relationships at earlier growth stages (figure 5(a)) show greater variation in slope and offset for the different field sites because of rapid changes in the canopy biomass. There are differences in crop growth stage between fields. The growth stage in field L21/25–6–7 was leaf production, whereas No34 was between leaf production and stem extension. At the later growth stages (figure 5(c)) there is a reduction in correlation post flowering because of the onset of crop senescence. These results are consistent with findings for wheat (Aase and Siddoway, 1981; Tucker *et al.*, 1980, 1981) and opium poppy



(a) Mature capsule volume

(b) Dry capsule yield

Figure 4: Summary of coefficients of determination (R^2) for the empirical linear relationship between NDVI at different poppy growth stages and: (a) mature capsule volume and (b) final dry capsule yield, for study fields. Poppy growth stages are: (0) emergence, (1) leaf production, (2) stem extension, (3) flower bud development, (4) flowering, (5) capsule development, (6) seed development, (7) senescence.

in North-Western China (Jia *et al.*, 2011). At flowering (figure 5(b)) the NDVI relationships for individual fields converge for mature capsule volume and dry capsule yield, indicating the possibility of generalised fits. Homogeneity of slope tests confirmed there were no significant differences (P=0.41, P=0.71 respectively) and figure 6 shows single regression lines through the data for NDVI against mature capsule volume (R^2=0.70) and NDVI against dry capsule yield (R^2=0.87).

3.7 *Yield estimate and mapping*

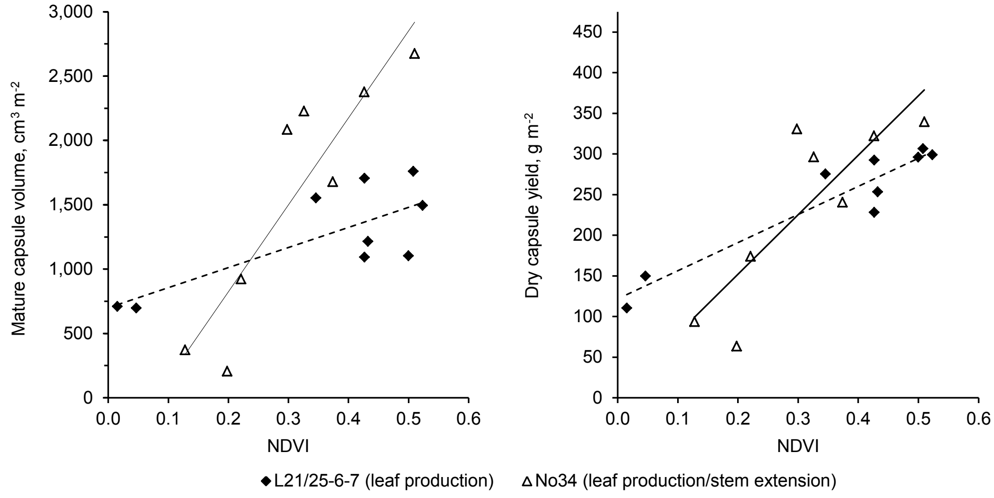
The field average poppy NDVI calculated from the image has no sampling error and when substituted into the regression relationship in equation 5 allows an un-biased estimate of the average mature capsule volume to be made. For L21 and 25–6–7, the average NDVI (excluding experimental areas) was 0.362 and when substitute into equation 6 gives an estimate of 1481 cm^3 m$^{-2}\pm$11.6% (95% CI) for the two fields. For comparison, the average mature capsule volume calculated from the sample alone is 1376 cm^3 m$^{-2}\pm$20.7% (95% CI), a lower estimate with wider confidence intervals than the regression estimate.

Estimates of dry capsule yield are similarly calculated by substituting the average NDVI (0.362) into the regression equation for dry capsule yield (R^2=0.70), shown in figure 6, which gives 2.60 t ha$^{-1}\pm$5.8% (95% CI), a narrower confidence interval than the mature capsule volume regression estimate ($\pm$11.6 %). Similarly to assess sample error, the sample dry capsule yield estimate is 2.44 t ha$^{-1}\pm$16.0% (95% CI), a higher estimate with wider confidence intervals that the regression estimate. For both yield indicators the regression estimate has a lower variance than the sample estimate.

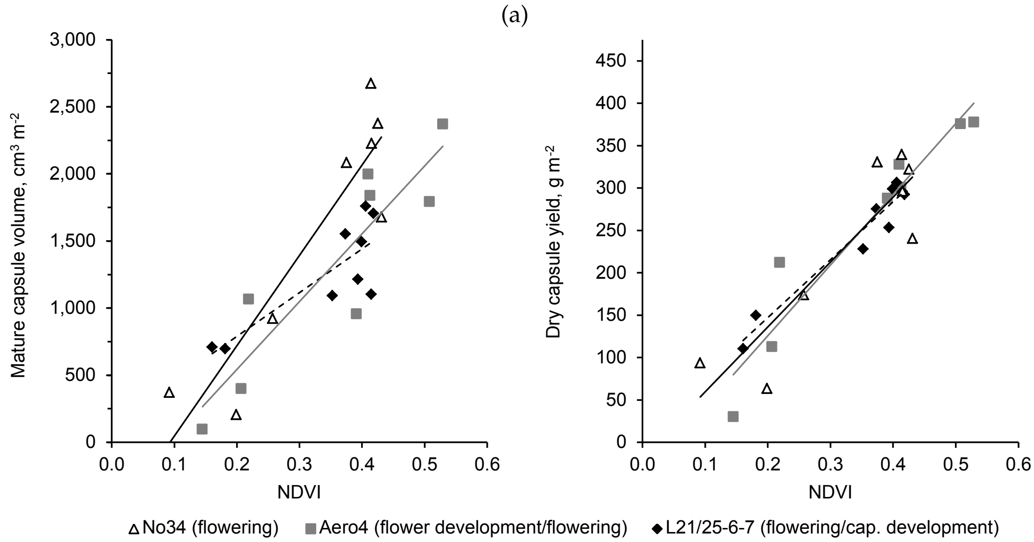
A map showing the spatial variation of poppy yield indicator can be produced by calculating the NDVI for each pixel in the ADP using the linear relationship from equation 5. As an example the generalised equation for mature capsule volume

$$V_c = 5051.5(\text{NDVI}) - 347.61 \qquad (6)$$

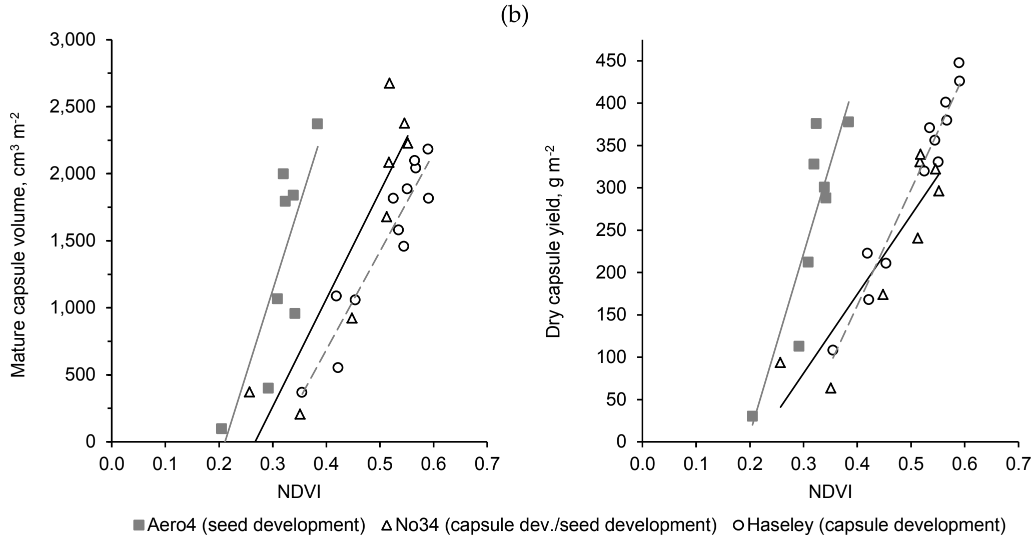
from figure 6 (R^2=0.70) was applied pixel-by-pixel to produce the yield indicator distribution map for fields L21 and 25–6–7 (figure 7). Negative values of NDVI were assumed to have zero yields. The mature capsule volume ranged from 0 to 2,464 cm^3 m^{-2}, the lower yielding areas are shown in dark brown through to higher yielding areas in dark green.



(a)



(b)



(c)

Figure 5: The empirical relationship between the poppy yield indicator mature capsule volume and NDVI (left), and dry capsule yield and NDVI (right) grouped by poppy growth stage: (a) leaf production/stem extension, (b) flowering and (c) capsule/seed development, for calibration sites.

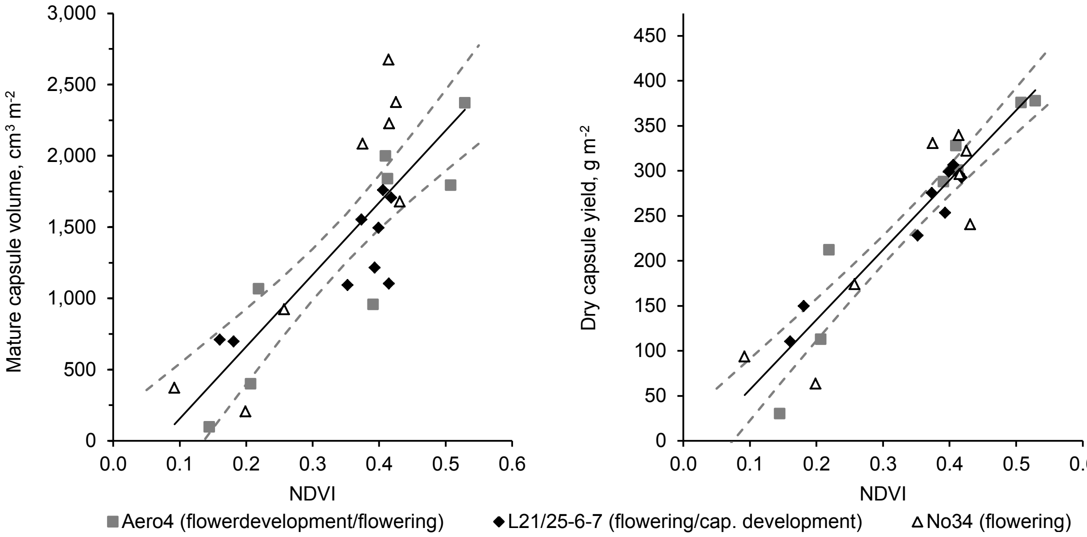


Figure 6: Generalised relationship between mature capsule volume and NDVI (left), and dry capsule yield and NDVI (right) from all calibration sites at flowering growth stage. Dashed lines show 95% confidence interval for the regression line.

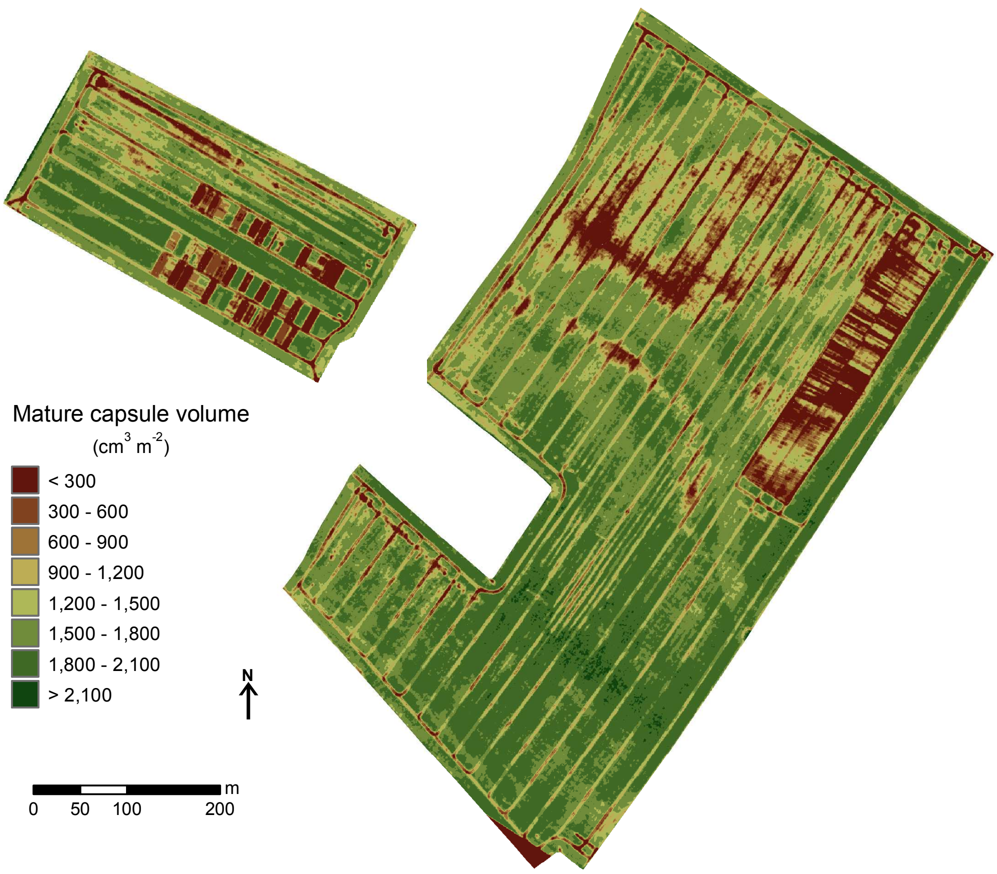


Figure 7: Map of poppy mature capsule volume for field L21 (left) and 25-6-7 (right) in Hampshire, UK. Two experimental plots (not discussed in this article) are visible in the south of L21 and east of 25-6-7, as variable yielding areas in regular block patterns between tractor tramlines.

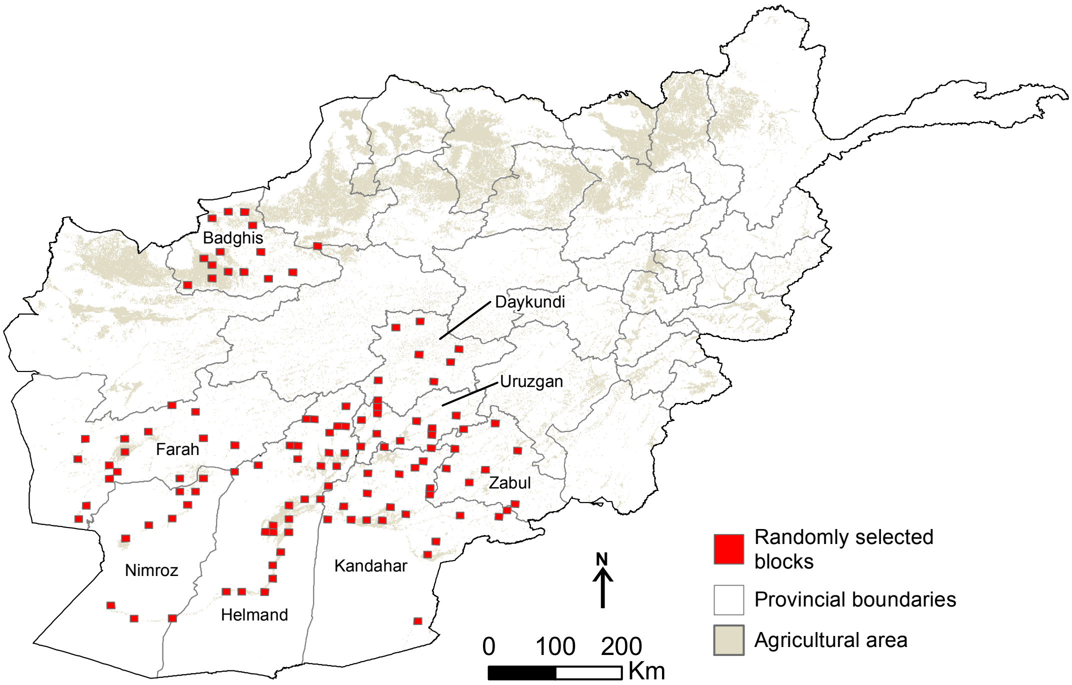


Figure 8: UNODC/MCN randomly selected image collection blocks in the main opium producing provinces of Afghanistan for 2011, adapted from UNODC (2011).

The tractor wheelings are visible at 28 m spacing as lower yielding light green lines. Two groups of experimental plots are seen in the south of the smaller field L21, and on the east side of the larger field 25–6–7. The southern half of field 25–6–7 yields better than the north. A curved linear feature of lower yield is visible across the middle of 25–6–7, which follows the course of a filled-in ditch.

4 Application in Afghanistan

The relationship between opium yield indicators and NDVI has practical significance for improving the yield estimate from the small, non-random sample collected in Afghanistan. The UNODC/MCN already collect VHR satellite imagery – suitable for calculating NDVI – at locations across Afghanistan for image interpretation of poppy crops. Images blocks are selected at random from a sample grid covering the agricultural areas of the main opium producing provinces (Figure 8). An unbiased estimate of the average opium yield per image could be obtained by calibrating the NDVI for each VHR image using a small number of high quality field observations. As the image blocks are selected at random, unbiased regional and national yield estimates could be made by substituting the average mature capsule volume from the images into equation 1.

Although Afghan opium crops develop in a similar way to those in the UK, the growing conditions and poppy varieties are different. The VHR satellite sensor characteristics also differ from the ADP used in the UK field trials. The spatial-resolution of the multispectral VHR imagery is coarser, ranging from 1.84 m to 3.22 m at nadir and the bandwidths in the R and NIR are wider (see table 4). The collection geometry is also more complex than the ADP as the sensors can be pointed off-nadir, acquiring images across

Table 4: Sensor ground sample distance (GSD) and bandwidths in the red (R) and near-infrared (NIR) for UNODC/MCN images selected for analysis.

Sensor	GSD m	Bandwidth, nm R	NIR	Province	Image date	Growth stage
WorldView-2	1.84	630–690	772–890	Herat	10-Apr-11	Flowering
IKONOS	3.28	632–698	757–853	Herat	17-Apr-11	Flowering
QuickBird2	2.44	630–690	760–900	Helmand	20-Apr-11	Capsule development
				Nangarhar	25-Apr-11	Capsule development

and along the satellite track. To investigate the proposed remote sensing approach in Afghanistan, the UNODC/MCN provided data from their 2011 and 2012 yield surveys together with coincident collections of multispectral VHR imagery and image interpretations of the active poppy crop. The yield data comprised capsule measurements from 1 m^2 quadrats, ground photography and the GPS coordinates of the sampled fields. The field locations were verified by cross-referencing the field coordinates with pan-sharpened imagery and ground photography. Each VHR scene was evaluated for poppy growth stage using the crop information system described in Simms *et al.* (2014) together with available ground photography. Of the 2011 and 2012 data, 4 image sites (IKONOS, Worldview–2 and 2x Quickbird2) contained identifiable sample fields and coincident imagery collected within the leaf development to capsule development growth stages of the poppy crop (table 4). The multispectral images for these sites were calibrated to top-of-atmosphere reflectance to minimise the difference in radiometry between the sensors. An NDVI image was then calculated for each scene by substituting the reflectance values into equation 4. Pan-sharpened imagery was used for visual image interpretation of the poppy crop canopy.

Figure 9 shows an example from the Quickbird2 image, located in the province of Nangarhar, of the frequency and spatial distribution of field average NDVI of poppy fields (top) compared with image-interpretation of crop quality (bottom). The poppy field NDVI ranges from 0.33 to 0.64 over a small geographical area, which is consistent with the variation in the quality of crops seen in Afghanistan. Fields with lower than average NDVI (insert 1) have a canopy with patches of bare soil, indicating a lower planting density or poorer crop, compared to uniform fields that have a higher than average NDVI (inset 2). The surveyed fields (marked a and b) are adjacent to each other and have NDVI values 0.51 and 0.48 respectively, with field b having the same value as the mean of all poppy fields within the image (0.48). The results show variation in the field average NDVI consistent with the image-interpreted quality of the crop.

The field average of mature capsule volume per unit area ($cm^3\ m^{-2}$) was calculated from the three 1 m^2 replicates within each ground surveyed field and plotted against the average NDVI for the field parcel. Field based averages of mature capsule volume were compared to field averages of NDVI because of insufficient support from the quadrat (3 per field on a random transect) observations to calibrate the VHR at the pixel scale (2–4 m). The results show an increase in NDVI with increased mature capsule volume at all 4 image sites but there were too few field observations per image to test the regression methodology.

Further analysis of the UNODC/MCN data were undertaken to investigate the suitability of the current ground observations for the calibration of VHR imagery. Within-field variation observed in the imagery, together with ground photography suggest that plot data might not be representative of the average capsule volume at the field scale in Afghanistan. In the UK field trials, spatial averaging of the quadrat triplet was used

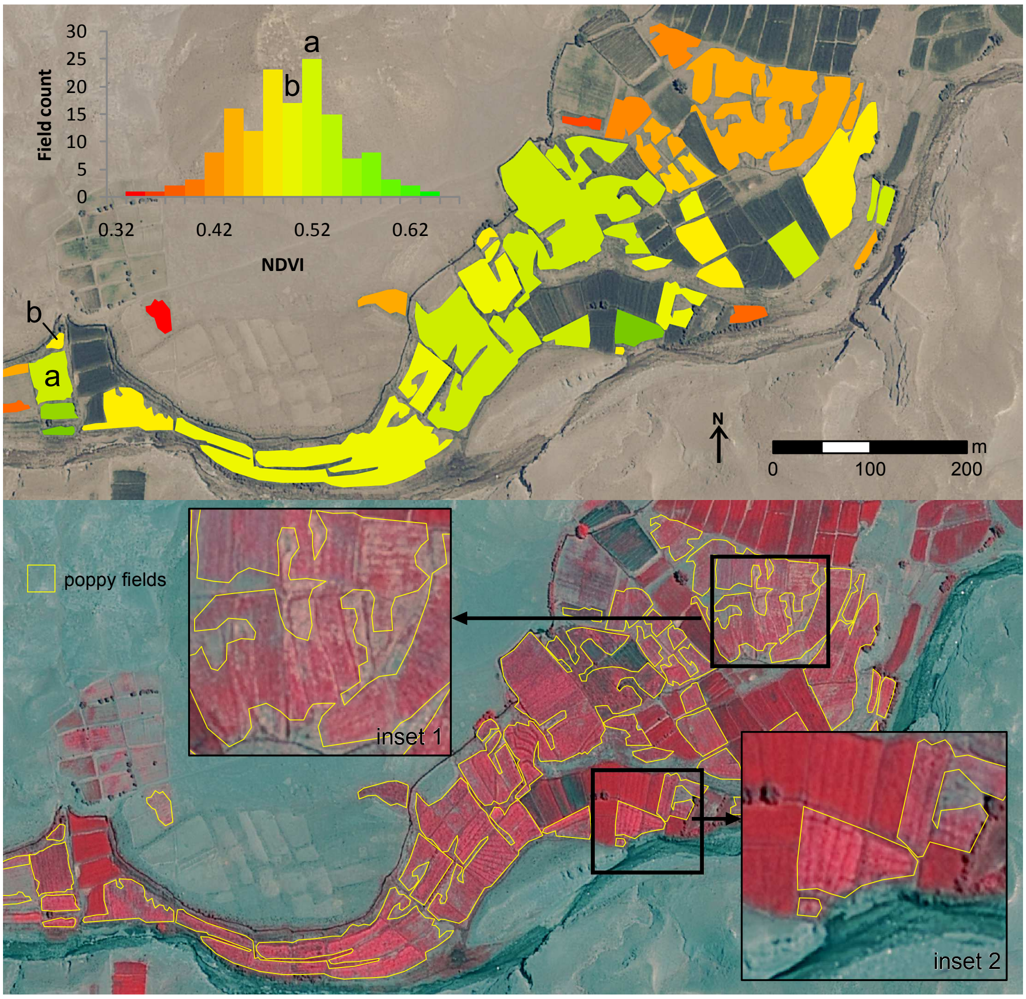


Figure 9: Spatial distribution of poppy field NDVI (top) and visual interpretation of crop quality (bottom) in subset of yield data from Nangarhar Province, eastern Afghanistan. Background image pan-sharpened true colour (top) and false colour (bottom) composite Quickbird2, 21 April 2011 (image ©UNODC/Ministry of Counter Narcotics, Government of Afghanistan).

to match the field observations to the imagery resolution and reduce any error in co-location. Adopting a similar approach in Afghanistan, using the spatial average of multiple quadrats at each sample location, would increase the number of observations available for regression. However, this would require sample sites to be accurately geo-located using GPS.

Thorough examination of geo-tagged ground photography supplied for 2012 shows irregularities in the spatial distribution of the quadrats within the sampled fields. In some areas they were clustered at the edges of fields or under tree cover and did not follow the protocol for positioning using a field transect. It is likely that surveyors were trying to reduce risk by moving to concealed areas of the field to take measurements. From our experience with field survey data in Afghanistan, the accuracy of measurements and data recording are affected by the security of the field survey teams. It is important to consider that any modifications to the survey protocol that significantly increase the time spent in each field could increase the risk and reduce the quality of the field data.

The current UNODC/MCN methodology for the selection of sample fields (representing poor, medium and good crops) relies on a subjective assessment of quality made by the surveyor. Since the poppy field NDVI is correlated to the variation in potential yield, appropriately timed VHR imagery could be used to target fields for sampling. Having prior knowledge of crop quality across an image would allow surveyors flexibility in selecting safer locations to collect field data without biasing the sample. In extreme cases a surveyor could target a single field, with an NDVI close to the mean for all poppy fields, to collect a representative measurement for the image.

The UK data shows stability in the relationship between yield indicators and NDVI across fields and between years for imagery coinciding with the flowering growth stage. A generalised equation would be an advantage for survey implementation as it would reduce the number of samples sites required to calibrate each image. Further work in Afghanistan is required to determine if a generalised function for a satellite sensor could be developed and used for calibration across multiple image sites, including the effect of sun-sensor-target geometry and the atmosphere on the linear relationship between NDVI and yield indicator. Accurately determining VHR imagery collection windows to target the poppy flowering period would be essential for this approach.

The investigation of opium yield estimation using remote sensing is ongoing. To date there has been insufficient data to demonstrate a regression methodology in Afghanistan, partly due to uncertainty in the quality of ground based observations and the availability of suitably timed coincident VHR imagery. The UNODC/MCN are seeking to improve data quality through better training and surveyor supervision (UNODC, 2012). The use of cameras with automatic geo-tagging in 2012 highlighted previously unidentified data quality issues and are an important step for providing confidence in ground data collection going forward.

In order to integrate the UNODC/MCN's current yield sample and VHR imagery the following conditions must be met: (1) ground data must be accurately geo-referenced; (2) The selection of ground survey sites must be made at locations that are representative of the range of poppy crop variation, with respect to NDVI, but not spatially auto-correlated; (3) ground measurements of poppy crop parameters must be accurately co-registered with ortho-rectified imagery; and (4) imagery used to derive NDVI should be targeted for collected around the flowering growth stage to maximise the correlation between yield indicators and NDVI.

5 Conclusions

The UK field trials showed good empirical relationships between imagery-derived NDVI and poppy yield indicators (mature capsule volume and dry capsule yield) for individual fields. The results suggested a generalised relationship (R^2>0.7) across all sampled fields and years during the 3–4 week period including the flowering growth stage of the crop. The correlation of NDVI with dry capsule volume was found to be better (higher R^2) than NDVI with mature capsule volume. The relationship between yield indicators and NDVI was used to map the within-field yield variability of UK poppy crops.

The optimum timing for image collection is during the 3–4 week period including flowering, which corresponds with the highest R^2 and greatest stability of the empirical relationship between NDVI and yield indicator.

In the UK poppy fields, the regression estimator adjusted the yield estimate from the sample and reduced the variance. This approach will correct for the bias in the sample distribution and increase the precision of the small non-random sample collected in Afghanistan, improving the accuracy of the yield estimate.

The feasibility of applying the yield regression estimator methodology in Afghanistan was investigated using 2011 and 2012 ground data and VHR satellite imagery collected by UNODC/MCN. The initial results were promising but there were too few observations per image to validate the methodology. Further data are required to demonstrate the approach, to investigate generalised calibration equations, and the targeted sampling of representative fields using VHR satellite imagery.

The current limitations of developing a remote sensing approach are related to the ability of surveyors to collect accurate ground measurements in a challenging and dangerous environment. We believe that the integration of the existing yearly VHR imagery collection with a smaller, accurate and targeted ground sample represents the best solution for improving opium yield estimates in Afghanistan.

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Towards improving the accuracy of opium yield estimates with remote sensing

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