Comparing dot grid sampling versus full area mapping for illicit crop monitoring in Bolivia

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ABSTRACT

Since 2002, the United Nations Office on Drugs and Crime (UNODC) has continuously supported annual surveys of coca cultivation in Bolivia. The mapping of coca fields is based on the visual interpretation of very high and high resolution satellite imagery. A full area mapping approach is applied, i.e. all fields where illicit crops are grown in a certain geographic region are visually interpreted and delineated on screen. The process bears the risk of several types of biases in the interpretation results and is time consuming. As an alternative a dot grid sampling approach was tested in order to diminish biases and to optimize the cost-accuracy-ratio of the visual interpretation in comparison to full area mapping. The paper summarizes the experiences and discusses the pros and cons of the approach for illicit crop monitoring under given conditions.

Keywords: remote sensing, illicit crop monitoring, dot grid sampling, coca cultivation, area estimates

PAPER

1. Introduction

The United Nations Office on Drugs and Crime (UNODC) supports monitoring systems of illicit crop production in the main drug-growing countries of the world. Jointly with the respective governments, UNODC produces annual illicit crop surveys for specific countries. The results are used for monitoring measures to reduce coca cultivation and global analysis of the drug situation, e.g. in the World Drug Report (UNODC, 2015).A key component to estimate plant-based drug production is the assessment of the area under cultivation. This is based on the visual interpretation of remotely sensed images. A full area mapping approach is followed. In such a case, all fields where illicit crops are grown are identified in the whole country or in pre-defined geographic regions. Polygons are visually interpreted and delineated on screen by qualified and trained staff who use classification keys to guarantee consistency between interpreters. Nevertheless, this process is time consuming and bears the risk of several types of bias in the interpretation results. Apart from thematic errors, systematic errors may occur when drawing the boundaries of the polygons, leading to inaccurate results.

Various internal tests have been carried out by UNODC and the University of Natural Resources and Life Sciences,Vienna (BOKU) to automatize the interpretation process using image processing techniques. These tests have shown that it is difficult to replace visual interpretation due to various reasons. On the one hand the characteristics of the plant (perennial, up to 4 harvests per year, with fields at different stages of development at any observation time, no unique spectral signature) make it difficult to detect plantations automatically.On the other hand the interpretation of fields strongly relies on the experience of the interpreter (knowledge of the geographic region, inclusion of context information) which makes it difficult to derive rules for an automated approach.

This study attempts to overcome the specific problem of one type of bias, with regard to the digitizing of the field boundaries (geometric errors), by using a sampling approach widely known as (squared) dot grid sampling.

Sampling methods are often applied successfully in the fields of forest inventory and agricultural statistics. The dot grid method originally was used in aerial photo interpretation as a simple and inexpensive tool for measuring land cover areas of irregularly shaped features (Lillesand et al., 2007). Forest areas are obtained in many national forest inventory schemes with aerial photo dot grid methods (Tomppo et al., 2010). An example for a method with points as sampling units in agricultural statistics is the EU-project LUCAS (Land Use/Cover Area frame statistical Survey; Bettio et al., 2002).

The assumption is that the dot grid estimate can bemore accurate than full area mapping due to the gain of time for the decision to classify the crop and due to the avoidance of delineation inaccuracies. No time has to be spent for delineating the boundaries. In case of illicit crop monitoring, dot grid sampling therefore could optimize the cost-accuracy-ratio of the visual interpretation in comparison to full area mapping.

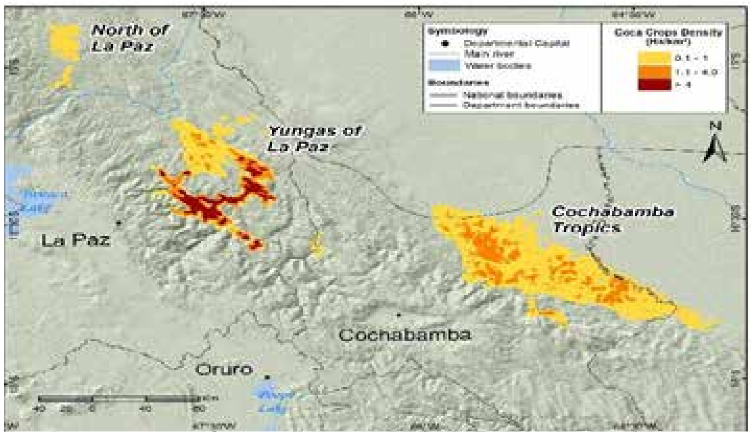
For testing the methodology two test sites were selected. One objective was to test the effect of different image types with different spatial resolutions on the interpretation process and accuracy. Secondly, the grid method was tested for different densities of coca fields, whichwill require different densities of dots to achieve the same accuracy and thuseffect the time to spend on conducting the interpretations.

It should be noted that interpretation errors (mistakes in the identification of coca crops) which may occur in the same way in the interpretation of full parcels and in the interpretation of (the surroundings of) single points (dots) are not considered in this report. The term "error" in this article refers to "sampling errors".

2. Coca growing in Bolivia

In Bolivia a monitoring system was established in 2001, resulting in first estimates in 2002. Coca is mainly grown in three geographic regions: Yungas ofLa Paz, Cochabamba Tropics and Norte of La Paz. In 2011 an area of 13.760 km² was covered with different types of very high spatial resolution satellite images (UNODC, 2012). The programme has used satellite images such asIkonos-GeoEye, Pleiades, Spot, RapidEye and WorldView and occasionally aerial photos. The satellite images are visually interpreted on screen supported by extensive field work. In 2012, 27.200 hectares of the area monitored were under coca bush cultivation. The density and sizes of the fields vary from region to region. Whereas in the Yungas ofLa Paz large fields or clusters of coca fields can be found (ranging from0.25 hectaresupto coca groupsof surfaces with 5 ha), fields in Cochabamba Tropics are relatively small (usually coca crops of 0.16 hectares) and are found dispersed in the landscape. Figure 1 shows a map of the main coca growing areas in Bolivia and the density given in hectares per km² calculated on the basis of a visual interpretation (UNODC,2012).

Figure 1 - Coca growing areas in Bolivia



3. Dot grid sampling

In the dotgrid method, the sample units to be interpreted are drawn in the form of a regular grid of points (dots). The population is assumed to be infinite, consisting of infinitesimal areal units (points) covering the area of interest. This infinite population is not really related to the pixels of the image: in visual interpretation of a digital image, the interpreter usually locates parcel boundaries with subpixel accuracy, taking into account a neighbourhood of pixels. Therefore, the interpreter does not assign pixels as a whole to a certain land cover class. Rather, a dot is assigned to a land cover class depending on its exact position within a pixel in a certain surrounding pixel pattern.Systematic sampling in a regular grid can be treated like simple random sampling if the units of the population can be assumed to be randomly distributed (Thompson, 1992). For actual land cover distribution patterns one cannot assume a truly random distribution of the units. The consequences of this will be mentioned below. The number of dots falling on the land cover class (crop type) to be monitored, divided by the total number of dots, gives an estimate of the proportion of the area covered by the specific land cover class. Applying this proportion to the surveyed area leads to the total crop area in the study area. We assume a square grid of dots superimposed to a total area of arbitrary shape.

$$p = \frac{A}{F}, \quad \hat{p} = \frac{\hat{n}_c}{n}, \quad \hat{A} = \hat{p} \cdot F$$

F…total area, A…crop area, p…fraction of crop area in total area (coca density), n…total number of dots (i.e. number of dots falling upon total area), n_c …number of dots falling upon coca fields. The hat symbol denotes a random variable.

The probability distribution of n_c is the binomial distribution. Its variance is calculated with:

$$\sigma_{\hat{n}_c}^2 = \mathrm{var}(\hat{n}_c) = n \cdot p \cdot (1-p), \quad \sigma_{\hat{p}}^2 = \mathrm{var}(\hat{p}) = \frac{p(1-p)}{n}, \quad \sigma_{\hat{A}} = \sigma_{\hat{p}} \cdot F$$

$\sigma_{\hat{n}_c}^2$ …variance of the number of dots falling upon coca

$\sigma_{\hat{A}}$… standard deviation of the crop area A due to sampling error

The required size of the sample (number of dots) to obtain a certain precision of area estimates with a certain confidence is the critical decision during the set up. The selection of an appropriate spacing between the dots depends on the coca density of the total area of investigation and on the error of the result that is acceptable.

In order to obtain a result (an estimate) for the coca area A with a standard deviation σ_A, i.e. a relative error (σ_A/A) of the coca area estimate, one has to use a grid with n dots in total:

$$n = \frac{p(1-p)}{\sigma_p^2} = \frac{p(1-p)}{\sigma_A^2 p^2} A^2 = \frac{1-p}{p}\left(\frac{A}{\sigma_A}\right)^2$$

The space between dots (dot grid spacing, s) thus has to be chosen according to

$$n \cdot s^2 = F = \frac{A}{p}, \quad s = \sqrt{\frac{A}{p \cdot n}} = \sigma_A \sqrt{\frac{1}{(1-p) \cdot A}} = \left(\frac{\sigma_A}{A}\right)\sqrt{\frac{p \cdot F}{(1-p)}}$$

The precision of the estimate will be higher for narrower dot grid spacing, with a larger sample.

Of course, at the start of a project, the fraction of crop area in total area, p, which is required to calculate a proper value of s, is not known. A likely, expected value for p has to be assumed here, e.g. the coca density determined in previous years.

This equation can also be used to calculate the relative sampling error (A/A) for a given dot grid spacing and a given fraction of crop area in total area, p (if this has finally been determined).It should be noted that there is a certain spatial correlation in land cover distribution patterns. Nearby units tend to have similar attributes. The assumption of random distribution of the units in the sample as mentioned above therefore is not quite justified. As a consequence, the dot grid method will tend to overestimate the variance of the area estimates. We are "on the safe side", underestimating the precision of the result rather than overestimating it. The area estimate itself is unbiased. There are various methods to obtain a better estimate of its variance in the case of spatial correlations (see e.g. Wolter, 1984).

If different coca cultivation densities prevail in different parts of the total area, a stratification approach might be followed.

4. Case studies

4.1 Test of different satellite imagery

The first test site is located in the Yungas ofla La Paz area which, is characterized by large fields, often clustered into larger areas.

A small area was selected where cloud free images of WorldView-2 (Acquisition date: 03-10-2011; spatial resolution: 0.5 meters) and RapidEye (Acquisition date: 31-05-2011; spatial resolution: 5 meters) were available; the images were orthorectified before doing the interpretations. As the area under crop is stable, the two different acquisition dates are comparable. The total area of interest comprises 1,259 ha of which 210 ha were used for coca plantations according to the results of the survey 2011 which was based on the visual interpretation of the WorldView-2 imagery. This serves as a reference data set. The two different types of images are shown in figure 2. Interpretations applying dot grid sampling were carried out by one interpreter familiar with the geographic region.

Two different settings for dot grid sampling were defined to demonstrate the effect of different dot spacings using different imagery. The parameters were selected to keep the amount of time necessary for the interpretation within an acceptable range. Two different distances between the dots were independently tested: 200 meters and 100 meters. The features of the grids and the results are shown in table 1.

Figure 2 - Dot grid sampling on WorldView-2 and RapidEye of the same coca growing area (yellow polygons: coca fields resulting from a visual interpretation of WV-2 data)

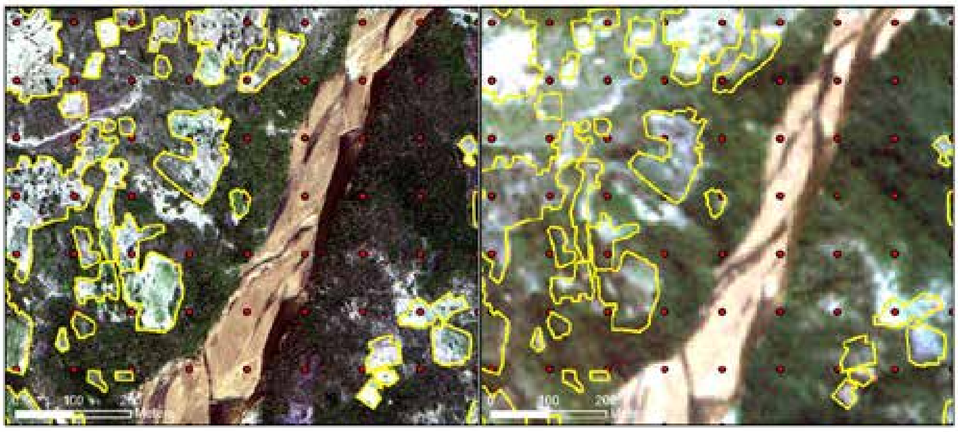


Table 1 - Interpretation results; case study 1, comparing images with different spatial resolution and two different grid spacings

Reference	Visual interpretation of WorldView-2 image (polygons)
Total area (ha)	547
Crop area from polygon interpret. (ha)	130.7
Number of polygons	187
Time needed for polygon interpretation	80 min

Results:

Sensor	WorldView-2		RapidEye	
Dot spacing (m)	100	200	100	200
Total number of dots	547	137	547	137
Number of dots falling upon coca fields	117	29	105	27
Estimated fraction of crop area in total area	0.2139	0.2117	0.1919	0.1971
Estimated crop area (ha)	117.00	115.79	105.00	107.80
Standard dev. of crop area	9.59	19.09	9.21	18.59
Relative sampling error (%)	8.20	16.49	8.77	17.24
Difference to polygon interpretation (%)	-10.48	-11.41	-19.66	-17.52
Time needed for dot interpretation	20min.	6 min.	15 min.	7 min.

4.2 Test in areas with different densities of coca fields

The objective of the second exercise was to test the dot grid approach in geographic regions with different coca field densities. The test areas are located in the Cochabamba Tropics which is characterized by small fields. An IKONOS image with a spatial resolution of 1 meterwas used. Each area comprises 10,000 ha. A 250 meter dot spacing was chosen as an example for dot grid interpretation with extreme time saving under the assumption that a relative sampling error of approximately 20% still might be acceptable for a first estimate.

Table 2 - Interpretation results; case study 2, with an Ikonos image and three areas with different coca density levels

Sensor	Low density	Medium density	High density
Total area (ha)	10000	10000	10000
Crop area from polygon interpret. (ha)	85.18	149.82	240.55
Number of polygons	718	1103	1766
Time needed for polygon interpretation	264 min	198 min	168 min
Dot spacing (m)	250	250	250
Total number of dots	1600	1600	1600
Results:			
Number of dots falling upon crop	15	23	29
Estimated fraction of crop area in total area	0.009	0.014	0.018
Estimated crop area (ha)	93.75	143.75	181.25
Standard dev. of crop area	24.09	29.76	33.35
Relative sampling error (%)	25.70	20.70	18.40
Difference to polygon interpretation (%)	+ 10.06	- 4,05	- 24.65
Time needed for dot interpretation	44.5 min	55.5 min	41.5 min

5. Discussion

The results show that the dot grid method severely reduces the time required for interpretation. In the examples given here, between approximately 10% (Table 1, 200meter spacing) and around 25% (Table 2) of the time required for full area (polygon) interpretation are sufficient for dot interpretation. The time saving obviously is higher for coarser dot grids (where fewer dots have to be interpreted) and for higher coca field densities (where more polygons have to be delineated). The time needed for the interpretation of 1 dot is approximately 2 seconds in all cases. The time needed to interpret and delineate 1 polygon is between 10 seconds (for smaller polygons) and 20 seconds (for larger polygons). The time saving is obtained at the expense of a certain sampling error. Basically, three types of errors have to be distinguished: interpretation errors, delineation errors, and sampling errors. We can assume that interpretation errors are of a similar magnitude in full area interpretation and in dot grid interpretation, if performed by the same interpreters. However, no information on this is at hand here, as exact data on the true coca areas are not available. In all cases with exception of the 100meter dot grid interpretation of RapidEye, the differences between polygon interpretation and dot grid interpretation can be assumed to be sampling errors:as can be seen from the tables, these differences between polygon interpretation and dot grid interpretation are usually smaller than 2 times the standard deviation of the crop area due to the sampling error.Taking the normal distribution as approximation to the binomial distribution, 95% of the results of dot grid interpretation should lie within this interval around the true value (here assumed to be the polygon result). The larger difference for the 100meter dot grid interpretation of RapidEye obviously is due to the systematic interpretation differences between WorldView-2 and on RapidEye. Most likely, the WorldView-2 results are more reliable, which is also supported by the assertions of the interpreters that it is more difficult to interpret coca on images of lower spatial resolution.

Fig. 3 - Comparison spacing/time for dot grid interpretation and time needed for interpretation and delineation of polygons in "Tropico de Cochabamba"

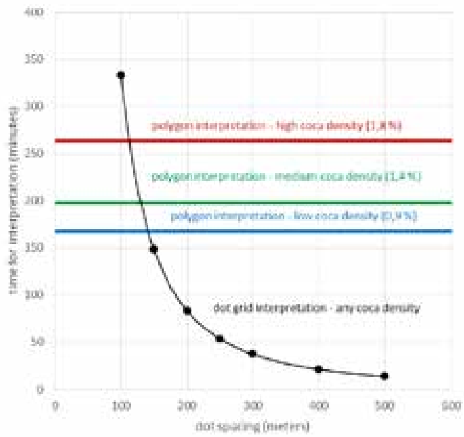


Fig. 4 - Comparison betweenrelative errors of different dot grid spacings for different coca density areas.

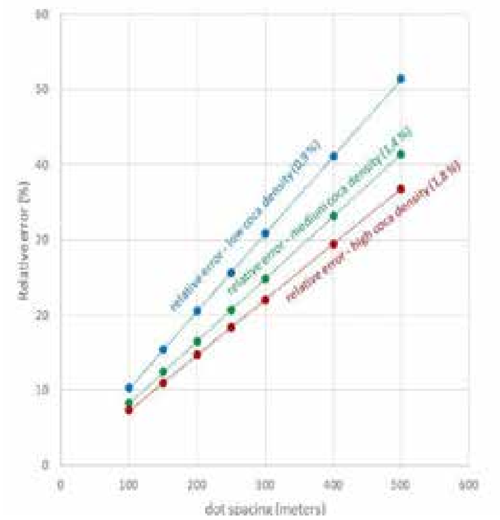


Figure 3 compares the time necessary to interpret dots compared to the time needed to interpret polygons for different coca field densities in the second test area. It can be seen that the dot grid interpretation becomes faster than polygon interpretation when the spacing between dots is larger than about 125 to 160 meters, depending on the coca field density. Of course, at the same time the relative sampling erroralso increases. It changes for low coca field densities from 10% (100 meter spacing) to 50% (500 meter spacing), for medium coca field densities from 8% (100 meter spacing) to 40% (500 meter spacing) and for high coca densities from 7% (100 meter spacing) to 37% (500 meter spacing). It follows from experiences in many fields of land cover mapping that it is hardly possible to reach thematic accuracies above the range of 80% to 90% (see e.g. Büttner and Maucha, 2006). Therefore, additional sampling errors up to 10% usually should be tolerable. Nevertheless, the additional sampling errors (figure 4) should be evaluated against the expected improvements for the interpretation accuracy, which can be considerably high but have not been quantified in this study.

6. Conclusion

Illicit crop area is usually determined by digitizing polygons on remotely sensed images, and by calculating the areas of the polygons. A map showing the crop areas is produced by this method. The method is time consuming and potentially inaccurate, as there may be systematic errors in delimiting the fields (drawing the boundaries of the polygons). If a detailed parcelmap is not needed, or if a sort of "soft map" (map of the density of coca plantations, without showing the exact locationsand boundaries of individual fields) is sufficient, a sampling approach (dot grid method) may give results of a higher accuracy than polygon delineation. Even if polygons are still required, dot-grid sampling can be an efficient method to test and train interpreters or to carry outa quick quality control.

The case studies have shown the pros and cons of the dot grid approach.The dot grid method is particularly favourable when interpreting areas with a high density of fields: in this case, a larger spacing ofthe dots can be chosen, and the substantial effort and time necessary for the polygon delineationisavoided. The tests in theYungas of La Paz area show that thedot grid interpretation can be more than 10 times faster than the full area interpretation with delineation of single fields. Interestingly there are hardly any time differences using the dot grid method for coca areas with different densities.

With the given crop densities for this case study, the maximum additional relative error of 10%, the following distances would be beneficial from a time-gaining point of view: 115 to 270 m for high density, 125 to 240 m for medium density, 140 to 190 m for low density.

An option to further speed up the dot grid interpretation is a pre-selection of points. Based on an automated land cover classification, a mask can be generated which includes for example dense forested areas, water bodies, built-up areas, rocks, etc.. Points falling upon such land cover units donot have to be interpreted.

Further research is necessary (a) on the variance that exist in polygon delineation, which has to be compared with the sampling error inthe dot grid method, and (b) on the potentials to quantify systematic biases by different interpreters and on methods to correct for that.

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