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THE USE OF AREA FRAMES AND REMOTE SENSING FOR AGRICULTURAL STATISTICS

Invited paper submitted by the University of Bologna, Italy*

Summary

An analysis of main characteristics of list, multiple and area frame sample surveys is performed, with reference to various experiences of agricultural surveys in the world. Some methods for improving ground crop area estimates with remote sensing data are also discussed with the aim of evaluating their performance. Particular attention is devoted to the use of the regression estimator and of the direct calibration estimator. The problem of assessing the cost-effectiveness of remote sensing is also faced.

Why using an area sample survey?

1. There are two meanings of an area sample survey, a restricted and a general meaning, as stated in FAO 1998. An area sample survey designates, in

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the general meaning, a probability sample survey in which, at least for one sampling stage, the sampling units are land areas. In a more restricted meaning, an area sample survey designates a probability sample survey in which the final stage sampling units are land areas called segments and the selection probabilities are proportional to their area measures. Both approaches foresee the subdivision of the analysed territory into non-overlapping pieces of land, according to specific criteria, to create the area sampling frame.

2. The different criteria for creating the area sampling frame and the different sample selection procedures have given rise to the different kinds of area sample surveys developed in many countries in the world; but which are the reasons why to use an area sample survey? In general, an area sample survey should be used to estimate agricultural variables where a list of farms is not available or where the rapid transformation of owner and farm structure does not allow creating and maintaining updated lists, like in some transition economy countries (Gallego et al. 1994).

3. Indeed, there are many other situations in which an area sample survey can perform better than a list sample survey. Particularly, a list frame is never complete. This means that, strictly speaking, a sample selected from a list cannot be considered probabilistic, because some farms have probability zero to be selected, since they are not in the list. Lists generally used are created by a complete census. In very favourable cases, with a relatively small number of large farms, like in Canada, the coverage of the census of agriculture is about 97 - 98% complete in the census year (Mayda and Chinnappa 1994), but most often the coverage is lower than 80% in the census year.

4. Farms not included in the lists tend to be smaller and with a different work organisation; thus they cannot be considered randomly excluded and estimates derived from samples selected from these lists can be seriously biased, especially some years after the census. In fact, updating a long list is a heavy and expensive work that, quite often, is not completely performed.

5. In the last years, many attempts have been done of using administrative data and tax files to update census lists (Trant and Whitridge, 1998). Some results look encouraging, but a very careful record linkage is necessary and the small farms tend to be absent from administrative and tax lists even more frequently than from census lists. Largest farms generally produce the biggest amount of most commodities, but the behaviour and the economic and social conditions of the other farms are generally very different.

Advantages of area frame sample designs

6. For the reasons described above, the guarantee of being based on a complete coverage in whatever year, even very far from the date at which the

area frame is created, is a very important quality of area probability sample surveys. After many years, the area sample can become inefficient, but still unbiased, unless the agricultural area has extended to areas previously considered non agricultural and excluded from the sampling frame.

7. Area sample surveys are generally considered less efficient than list sample ones, since a list frame often includes auxiliary information concerning the holdings that can be used in the sample design (e.g. for stratification or selection probability proportional to size etc.). But this efficiency is very sensitive to obsolescence. In fact, after some time, some farms included in the list do not exist at the moment of the survey, while new ones have not been identified for inclusion. The expansion factors are therefore no longer adequate. In addition, the stratification based on certain characteristics (i.e. arable land) of farms may be not very efficient, because of changes in the farm structure.

8. An example of the effects of obsolescence of a list frame was given in Emilia Romagna administrative region, in Italy, where a comparison between an area and a list sample design was performed in terms of estimates precision (Carfagna et al. 1992a). The list was the result of the agricultural census performed in 1980 and someway updated. A stratified random sampling of 1700 farms was drawn. The stratification of the list was based on the farm size.

9. In the same region, the land use of 313 segments with permanent physical boundaries (92 of 100 ha and 221 of 50 ha) was drawn on aerial photographs. Finally, 617 farmers, selected by points from the 313 segments, were interviewed. For the main crops, the precision of the estimates produced by the three methods was comparable.

10. Another important advantage of area sample designs is that the use of aerial photographs, indicating the fields, allows objective and timely estimates of areas of the different agricultural land uses, independently of the farmers, and helps to reduce non sampling errors concerning information collected through farmers interviews. Aerial photographs and remote sensing data, on which many area sample designs are based, are becoming cheaper and more accurate. Besides, area measurements on aerial photographs are a good basis for data imputation for non-respondents. Yield estimates can also be performed independently of farmers, through crop cutting yield surveys or experts estimates on a subset of fields in selected segments.

11. Finally, versatility of area frames allows to collect not only information concerning agricultural variables, but also data on environmental items, such as level of pesticides in the soil, deforestation, change in number and kind of linear elements (edges, roads, channels) and so on. Environmental data collection is favoured by the possibility of obtaining the proper spatial distribution of selected segments. In general, a scattered distribution of area sampling units should be used for highly autocorrelated variables. It can be guaranteed by detailed stratification or systematic

sampling. On the contrary, a clustered distribution is better for items with low or negative spatial autocorrelation. It can be obtained by single stage cluster sampling or two stage sampling. Obviously, when delineating an area sample design, these general considerations must be combined with a cost function expressing the link between travel and ground survey costs (for more details see Carfagna 1998).

Disadvantages of area frame sample designs

12. Area sample designs also have some disadvantages. If a general purpose agricultural survey has to be performed, interviews with farmers are necessary. When farmers live far from their farms and carry out extensive agriculture, their identification can be a long and expensive operation and missing data tend to be relevant (Italian Ministry of Agriculture and Forestry, 1995).

13. The necessity of cartographic material and the cost of starting up the survey program (particularly where an area frame with physical boundaries has to be constructed) are also disadvantages of area sample designs.

14. Finally, area sample surveys are sensitive to outliers; in fact unstable estimates can be produced when extremely large operations are in the sample segments.

General purpose multiple frames surveys

15. The most widespread way to avoid estimates instability and to improve their precision is the use of multiple frames sample surveys. The following procedure is generally adopted:

- A list of very large agricultural holdings and of holdings that produce rare items is updated and sampled (sometimes completely enumerated).

- Holdings included in the list sample are eliminated from the area sample.

- Area and list survey estimates are combined to produce the final estimate (Cicchitelli 1999).

16. The basic idea is that a complete list of very large agricultural holdings and of holdings that produce rare items is easier to create and update than the list of all agricultural holdings. Estimates instability is very relevant for commodities associated with small portions of area - for example, in some regions, holdings with cattle breeding occupy small agricultural areas - since their selection probabilities are small and consequently their expansion factors are large.

17. In some European countries, holdings with cattle breeding have often no Utilised Agricultural Area (UAA); thus cattle tend to be underestimated if selection probabilities of the sampling design are proportional to the UAA of the holding. In such situation, estimates produced through an area frame sample design might not only be unstable, but also biased (Carfagna *et al.* 1992a, b).

18. Furthermore, multiple frame sample designs are also more efficient than simple area frame designs for all commodities that are highly concentrated in a small number of farms and for rare items, if a specific list is created.

19. In a multiple frame survey process, a very crucial step is the detection of the overlap between the list frame and the area sample. In fact, the record linkage is not easy and sometimes it is even impossible due to laws on confidentiality.

20. Another kind of multiple frame survey is used in the U.S. and was conducted in Canada till 1995 (FAO 1998). In these countries, the list component of the sample survey is very big and the main rule of non-overlapping farms found through the area survey is to account for new births and list under-coverage.

General purpose area frame surveys

21. Many countries carry out general purpose agricultural surveys, concerning almost all agricultural commodities, on the basis of area frames only. The main reason is the difficulty to create and update a good list of biggest farms. Area frames with permanent physical boundaries are generally used in these cases, but in some circumstances, unclustered point sampling is preferred.

22. There are two ways of performing unclustered point sampling. In the first way, the enumerator delineates a circle around the selected point and enumerates all farming operations that have land within the circle. In the second way, the enumerator determines who operates the land where the point falls and enumerates only the one operator to determine the agricultural activity on the entire farm.

23. The latter sample design corresponds to farm selection with probability proportional to the size of the farm. It is efficient only if the spatial autocorrelation between farms in a stratum is very high, since travelling costs are high. Moreover, in case the farmer cannot be found or refuses to co-operate, the travel is useless, since missing data correspond to the point. Thus, if a fixed budget is considered, this sample design does not maximise estimate precision.

24. Unclustered point sampling carried out in the first way is not very different from an area frame based on square segments; advantages and disadvantages are the same in case the circle is drawn on an aerial photography in the office. If aerial photography is not used, or the circle is drawn directly by the enumerator, then non-sampling errors are probably much higher.

Special purpose area frame surveys

25. As stated in the previous paragraphs, area frame sample surveys produce unstable estimates mainly for specific items. For main land uses, not concentrated in a very small number of holdings, instability problems are not relevant. Thus, since the main interest of some European countries, such as France, Greece, Italy and Spain, is to produce timely area estimates for the main land uses, they have adopted area frame sample surveys. Area estimation for the main land uses independently of farmers' interview is an important task in EU countries, for monitoring subsidies based on acreage.

26. In Italy, crop area and production are the variables of interest and a stratified area sample survey of segments of a target size of 50 ha, with permanent physical boundaries, is performed, similar to the approach of the United States. During the ground survey, field limits in selected segments are drawn on a printout of an aerial photograph and measured in the office (FAO 1998).

27. Crop areas are estimated in Spain and Greece through an area sample survey of square segments of 49 ha. The sampling selection procedure in Spain is non-stratified aligned systematic sampling by blocks of three replicates with a distance threshold. Fields mapping is foreseen (ibid.). The system is very similar to the one developed by the Regional Inventory action of the MARS project (Taylor et al. 1997).

28. Finally, the French TER-UTI system is carried out for estimating land uses and land covers and is based on aligned systematic sampling by blocks of segments of 1800 m × 1800 m, where 36 points on a regular grid are visited. The observed area around the point is about 9 m^2 in homogeneous tracts. No stratification is adopted (Gay and Porchier, 1998).

Comparison between segments with physical boundaries, square segments and points clustered in segments

29. First of all, it can be noticed that the Greek, the Spanish and the French systems are based on a regular grid approach, while the Italian project is based on segments with physical boundaries. Area frame construction and sample selection tend to be simpler, faster and cheaper when the regular grid approach is adopted, instead of segments with physical

boundaries. Some experiments were done in Emilia Romagna, Italy and in Navarra, Spain (Gonzalez Alonso et al. 1991) to compare the performance of square segments and segments with physical boundaries of the same target size. The comparison has shown that estimates coefficients of variation are similar.

30. On the other hand, the method of square segments presents some disadvantages, mainly due to the difficulty of locating the segments on the ground. Identifying theoretical limits on the ground is more difficult than recognising physical, permanent boundaries. Thus, non sampling errors may be much more frequent.

31. If, instead of mapping all the fields in a segment on an aerial photograph, only a sample of points is observed, location errors tend to be higher, since points are not easily located on the ground. During the quality control process, it is difficult to distinguish between location and identification errors. If only points are visited, an additional source of variability is introduced, but costs can be reduced for the same segment size, because the task of observing points is faster than delineating and digitising segment; thus a larger segment can be surveyed with the same cost. In areas with very large fields, not much information is lost, since non observed areas around selected point tend to present the same land use of the points.

Possible ways to combine remote sensing and area frame sample designs

32. Remote sensing is very useful for the production of agricultural statistics, particularly for large territories. In fact, it can be a precious base for estimating parameters of spatial variables, through area frame survey designs. Nowadays, when an area frame with permanent physical boundaries is constructed, strata and counting units are drawn on remote sensing images, through a manual or computer assisted procedure (FAO 1998).

33. Stratification is the most widespread way of improving estimate precision, also when area frames with square segments are used. Remote sensing is very useful for this application and the cost is, not particularly high. Another way of improving estimates precision is through the use of remote sensing data as auxiliary variables. The usefulness of such auxiliary variables is a function of the correlation with estimated variables. Besides these traditional ways of using remote sensing data, some others are outlined in the next paragraphs.

34. Generally, remote sensing data should not be used as a direct tool for crop area estimation. In fact, sometimes, a supervised classification of remote sensing data is directly used to estimate the area Z_c covered by a land use c in a region. The estimator can be written as:

$$\hat{Z}_c = \frac{Npix_c}{Npix} D \; .$$

where $Npix_c$ is the number of pixels classified into the land use *c*, *Npix* is the total number of classified pixels and *D* is the total area of the region. This estimator is known to be strongly biased (Card 1982, Hay 1988, Czaplewski and Catts 1992). The estimates are reasonably good only if spectral signatures are very clearly discriminated; for example estimating the area of irrigated crops on a summer image in a very dry region.

35. Similar problems arise when photo-interpretation of satellite images is used for crop area estimation, since photo-interpretation errors tend to be systematic and, generally, there is no compensation between the areas of *c* interpreted as *c'* and the areas of *c'* interpreted as *c* (Carfagna and Gallego, 1999).

Remote sensing images for area frame stratification

36. For agricultural estimates, an efficient and low cost stratification is based on percentages of agriculture, often derived from photo-interpretation of remote sensing images or of aerial photos. In remote sensing projects, the effectiveness of stratification is usually assessed by the relative efficiency, which is the ratio between the variance of the estimators without and with stratification, given by:

$$h_{strat} = \frac{Var(\hat{Z}_{ran})}{Var(\hat{Z}_{strat})}$$

37. However, the same reduction in variance could also be achieved by increasing the size of the ground survey sample of a number n_1 of segments. Thus, the stratification will be economical if the ratio between the cost of the stratification and the number of years that the stratification is likely to be used is smaller than the cost of surveying n_1 additional segments.

38. If crop estimates have to be produced, remote sensing images photo-interpretation is often used for excluding some areas from surveyed area, and no segments are allocated in non agricultural area. In some cases, when detailed information is used and combined with other data such as altitude, this is a good practice to reduce survey cost. However, the relative efficiency is underestimated, since presumed non agricultural segments cannot contribute to calculating the variance of the estimates. To allow a better estimate of the relative efficiency and to verify the presence of some small agricultural areas, at least a very small number of sample segments should be allocated on areas classified as non-agricultural.

39. When not very detailed information is used, eliminating some areas from sampled strata is risky, since very often agricultural fields are present in strata that have been identified as “non agricultural”. CORINE Land Cover

(obtained from photo-interpretation of remote sensing data, the smallest unit mapped has a surface of 25 ha) has been used in a study, to identify “agricultural” and “non agricultural” areas. 2357 of the 8017 segments surveyed in Spain in 1992 turned out to be located in the areas classified as “non agricultural” by CORINE Land Cover. Estimates performed using only segments in agricultural stratum are much lower than the ones obtained using all the segments. A bias around 4% has been detected for most crops in 1992 and in 1993, an unacceptable bias for crops estimated with a coefficient of variation of 1% or 2% (Gallego et al. 1998).

Dynamic stratification

40. The Italian Ministry of Agriculture performed an experiment of a very special kind of stratification, called dynamic stratification, in the administrative region Emilia Romagna in 1995. The aim was to estimate areas of the main crops. Points were systematically distributed on the region by a regular grid. The dynamic stratification was carried out after sample selection, on the basis of photo-interpretation of SPOT satellite images. The stratification concerned the presence of winter crops, summer crops or permanent crops. In June, a first ground survey was conducted only on points with winter crops, permanent crops and doubtful points. Only points with summer crops were visited during the second ground survey. Points were located on the ground through a GPS.

41. Results appeared very encouraging, since the stratification process is fast and cost-effective when compared with ground survey. Estimates and their variances, however, were calculated treating photo-interpreted points as if they were surveyed on the ground. A more accurate analysis is needed to evaluate possible bias due to photo-interpretation.

Stratification of an area frame based on a regular grid

42. When an area frame is based on square segments without permanent physical boundaries, the area frame construction doesn't require the use of remote sensing data. Anyway, images photo-interpretation can be used to produce land cover maps that allow to subdivide the population of segments into non-overlapping sub-regions in such a way that the variation of crop area per segment within each stratum is low. Practically, a square grid is overlaid on the land cover map. The attribution of each segment to a stratum is made according to a specific criterion.

43. The criterion of majority is generally used. In essence, the stratification is adapted to the sampling grid. Each square of the sampling grid is simply attributed to the stratum with the highest share, but part of the information in the stratification is lost. This and other criteria were tested in the European Union using CORINE land cover map (Gallego et al., 1998). CORINE Land Cover is an environment oriented database, and its

nomenclature has been established according to this main orientation, thus it wasn't produced to stratify the territory for crop estimation. However, it turned out that CORINE land cover is useful to improve estimates precision.

44. The second criterion was keeping only the largest piece of the segment in one stratum and discarding all other pieces. The last criterion was splitting border segments into pieces that belong to different strata. This option keeps more strata information, but may be complex to manage. Estimates of the different strata are not independent, since the selection of segments cannot be independent in the different strata; hence this is not properly a stratification and the total variance cannot be calculated simply by combining the estimator variances of the different strata. Covariances should here be taken into account.

45. "The large pieces approach" has given the best relative efficiencies, a bit higher than the efficiencies obtained with the majority criterion. The third approach has given moderate values for the relative efficiency of stratification, probably due to the poor relative location of ground survey units and strata limits. Relative efficiencies have been computed on the basis of a ground survey carried out in Spain in 1993.

46. Where the sample survey is performed on points clustered in square segments, problems involved in the use of a stratification are similar to the ones described for completely enumerated square segments; but they are emphasised by the large size of segments.

47. Another possibility to use CORINE database for crop estimation is creating an agricultural intensity index, that is a mix of CORINE categories that are supposed to be more or less made of arable land (Gallego et al., 1998). Arable non irrigated land, rice, and other arable irrigated land should be completely agricultural categories. Other two categories are supposed to be partially made of arable land: “mixture of arable and permanent crops” and “heterogeneous agriculture”. No explicit information is available about the real share of arable land in each of these classes; thus, a hypothesis was made and the following agricultural index was created:

Agriculture intensity index = arable non irrigated + arable irrigated + rice + vineyard/4 + (heterogeneous agriculture)/4

48. Four strata were created using the agricultural intensity index. Then each segment in the study area was assigned to one of the four strata, according to the value of the index. Relative efficiencies for main crops were computed through ground survey data collected on 10,600 segments in an area of about 350,000 km^2 in Spain. Relative efficiencies (table 1) suggest that, even if the stratification is based on a land cover map created for other purposes, it can help a lot to improve estimates precision.

Table 1: Relative efficiencies of stratification, based on the agriculture intensity index, for main crops in 1993

Main crops	Relative efficiencies
Wheat	2.21
Barley	1.51
Cereals	2.18
Sunflower	1.74
Sugar beet	1.74
Fallow	1.18

From Gallego *et al*. 1998

Relative efficiency of stratification in surveys based on square segments and on segments with physical boundaries

49. An experiment was performed in some test sites in France, Greece, Italy, Germany and Spain, in the frame of the “Regional Inventories” action of the MARS project (Taylor et al. 1997). The stratification was based on different information sources in the different countries. Relative efficiency of stratification was calculated for each crop in each administrative region. The best results were reached using photo-interpretation of remote sensing images.

50. Square segments were used, except in Emilia Romagna, where in 1990 square segments were replaced with segments with physical boundaries, with a methodology similar to the one applied in the United States. Theoretically, the land use stratification carried out for an area frame with physical boundaries is more efficient, than using square segments. The reason is that the latter are generally attributed to the different strata on the basis of majority, which results in higher variability within strata. However, results don't support this thesis, since relative efficiency decreased in Emilia Romagna in 1990, as shown in table 2.

51. A synthetic index of relative efficiency of stratification is used ($h_{weighted}$). It is a weighted average of relative efficiencies of stratification for the different crops in each study site (h_{strat}), with the weighting according to the proportion (p) of the crop in each study site, as follows:

$$h_{weighted} = \frac{\sum p h_{strat}}{\sum p}$$

Cases with crops covering less than 1 % of the study area not included.

Table 2. Weighted relative efficiencies of stratification for study sites, across all crops

	1988	1989	1990
Centre (France)	1.41	1.46	Abandoned
Bavaria (Germany)	1.44	1.59	1.46
Emilia Romagna (Italy)	1.31	1.31	1.18
Castilla león (Spain)	1.53	1.46	1.54
Macedonia (Greece)	1.49	1.67	1.70
Overall	1.43	1.49	1.47

From Taylor *et al.* 1997

52. In the Italian administrative region Emilia Romagna, as from 1990, the stratification was based on photo-interpretation of satellite imagery, as well as in the Greek region Macedonia; but in the latter site results were better. In Macedonia, strata were based on clear geographical distinction between mountains and areas of irrigated and non-irrigated agriculture, which had different crops. In the other study sites, strata were defined by grouping existing small administrative sub-regions according to the relative proportions of the main crops of interest within them.

Relative efficiency of stratification in the Italian project

53. We have analysed relative efficiencies of stratification in the Italian project, where the area frame currently used was created in 1992 through photo-interpretation of SPOT satellite images at a scale 1:25,000 and the usual procedure of identification of primary sampling units with permanent physical boundaries. The stratification was based on land use. We have calculated the weighted relative efficiencies of stratification for the main crops in Italy (tab. 3). For each crop, relative efficiencies in the different administrative regions have been summarised using the percentages of crop in the regions as weights.

Table 3. Weighted relative efficiencies of stratification for main crops, across Italian administrative regions in 1997 and 1998

Crops	Area (ha) 1997	Rel. Eff. 1997	Rel. Eff. 1998
Durum wheat	1,644,324	1.45	1.59
Soft wheat	566,798	1.12	1.10
Barley	353,553	1.03	1.05
Colza	39,250	1.20	1.02
Maize	1,120,388	1.14	1.21
Sunflower	276,433	1.04	1.12
Soy been	338,683	1.12	1.15
Sugar beet	300,857	1.13	1.17
Tomato	71,875	1.06	1.09
Tobacco	46,385	0.99	0.94
Italy	4,758,546	1.23	1.29

54. Relative efficiencies are low, except for durum wheat. The main reason for these low relative efficiencies is the fact that one of the aims of the stratification based on the land use was the identification of non-agricultural areas, where no segments were allocated. This procedure reduces the ground survey cost, but determines an underestimation of the variance without stratification and, consequently, of the relative efficiency of stratification.

55. The land use stratification based on photo-interpretation of remote sensing images created strata with different rates of permanent and annual crops; but did not discriminate between annual crops. To improve relative efficiencies, land use strata should be subdivided into areas with similar association of the different crops.

56. An experiment carried out in Marche region (Italy) in 1992 showed that a cluster of municipalities, based on the percentages of main crops (derived from the census of agriculture performed in 1990), could improve considerably relative efficiencies of stratification for annual crops. The final stratification was the result of the intersection of the two kinds of stratification. The effect of the cluster of municipalities on the efficiency of stratification was still evident in 1998 (table 4), although the spatial distribution of annual crops tends to change faster than the rate of annual and permanent crops.

Table 4 Relative Efficiencies of Land Use Stratification, Cluster of Municipality and Final Stratification for acreage estimation of various crops in Marche region

Crop	Rel. eff. of Land use stratification in 1992	Rel. eff. of cluster of Municipality in 1992	Rel. eff. of Final stratification in 1992	Rel. eff. of final stratification in 1998
Soft wheat	1.00	1.24	1.27	1.26
Durum wheat	1.04	1.57	1.60	1.67
Barley	1.06	0.99	1.10	1.18
Sugar-beet	1.02	1.42	1.45	1.61
Vineyard	1.62	1.29	1.40	Not available
Olive trees	1.37	1.04	1.11	Not available
Orchards	1.33	1.14	1.17	Not available
Colza	Not available	Not available	Not available	1.03
Maize	Not available	Not available	Not available	1.03
Sunflower	Not available	Not available	Not available	1.06
Soya	Not available	Not available	Not available	1.04
Tomato	Not available	Not available	Not available	1.03

The use of remote sensing data for optimising an area sample design

57. The precision of estimates of an area survey is heavily influenced by the sample design. If a previous survey has been carried out, then these data can be used to improve the sample design (Carfagna and Gallego 1995 a, b).

58. One of the ways to use previous data is calculating the correlograms for each observed variable. In fact, an analysis of correlograms gives many suggestions for the optimum segment size and for the number of stages to adopt to maximise the precision of estimates under a fixed budget and a given cost function (see Carfagna 1998).

59. In a similar way, when data have not been collected by a previous sample survey, photo-interpretation of remote sensing data can be used to calculate correlograms. If the correspondence between photo-interpreted classes and the variables of interest is not perfect, then the results can be influenced. Usually, the classes of the photo-interpretation are aggregations of the variables of interest; thus the sample design is optimised for these aggregations. Besides, photo-interpreted data can be used as previous survey data only if the difference between their scale and the scale of data acquisition in the sample survey is not too big.

60. The use of CORINE Land Cover database for determining an optimum sample design is being tested now in the FMERS project (Forest Monitoring in Europe with Remote Sensing) of the Joint Research Centre/CEO.

Selection probability proportional to an index of agriculture intensity

61. An experiment carried out on data collected in Spain in 1992 showed that proportional probability sampling is very efficient when the ancillary information is highly accurate. 8017 segments, on which a ground survey was carried out, were used as the whole population. From these segments, a sub-sample of 80 segments was selected, with probability proportional to total arable land observed on the 8017 segments in 1992. Then, a simulation allowed to estimate the relative efficiencies (compared with simple random sampling) for main crop area estimates and for crop area changes. Values obtained were high: minimum value 2.39, maximum value 7.07, mean 3.91 and median 3.08 (Carfagna and Gallego, 1998).

62. When this kind of previous information is not available, remote sensing data can be used for creating an index of agriculture intensity, that should be calculated for each cell of a regular grid overlaid on the remote sensing image. The size of the cells should be the same as the segments of the ground survey. Then, a sample of segments can be selected with a probability proportional to the adopted index. If, for reasons of economy, the information necessary to calculate the index can be collected only on a sample of the cells of the regular grid, a two-phase sampling can be set up. The second phase is a sub-sampling with a probability proportional to the index. Indeed, detailed information is needed for this procedure; in fact, an experiment carried out using CORINE Land Cover to calculate the index of agricultural intensity and selecting the sub-sample of 80 segments with probability proportional to the index, has given very bad results. Many values of the relative efficiency were below one, minimum value 0.01, maximum value 3.25, mean 0.65 and median 0.43. Better results have been reached transforming the index into four strata, as previously described.

The use of remote sensing data as auxiliary variables for agricultural statistics

63. The use of remote sensing data as auxiliary variables allows improving the precision of estimates based on a ground survey carried out on a sample of segments with physical or theoretical boundaries.

64. If the precision to be reached for the estimates is fixed, then the use of auxiliary variables can reduce the amount of ground data to be collected. On the contrary, if the sample size is fixed, it allows improving the precision of estimates. Auxiliary variables generally involved are thematic maps created by the classification of satellite images, which is often performed by maximum likelihood. The regression estimator is the most widespread way of using remote sensing data as auxiliary variable to improve the precision of estimates (Cochran, 1977, Chhikara et al. 1986, Consorzio ITA 1987, González and Cuevas 1993, Gallego et al. 1993). In some areas,

experiments have been done to test the performance of a calibration estimator based on confusion matrixes (Hay, 1988, 1989; Jupp, 1989).

Regression estimators

65. The regression correction of survey estimates is a classic technique (Cochran, 1977) to estimate the mean of a variable *Y* known for the n units of a sample, by using an auxiliary variable *X* known for the *N* elements of the whole population and correlated with *Y*.

66. The area estimates are obtained separately for each crop *c*; hence we shall drop the index *c*. y_i is the area of land use *c* in segment *i* (from the ground survey); the auxiliary variable x_i is most often the number of pixels classified into crop *c*.

67. The linear regression estimator of the population mean of Y is:

$$\bar{y}_{reg} = \bar{y} + b\left(\bar{X} - \bar{x}\right)$$

where:

$\bar{y}_{reg}$ = regression estimator of the population mean (the average area of crop *c* per segment in the population);

$\bar{y}$ = average area of crop *c* per segment estimated from the ground survey;

b = angular coefficient of the regression line;

$\bar{x}$ = average number of pixels per segment classified into crop *c* in selected segments, determined by classification of satellite data;

$\bar{X}$ = average number of pixels per segment classified into crop *c* in the population, determined by classification of satellite data.

68. When the angular coefficient of the regression line has a previously fixed value (e.g. *b* is estimated from another population or from a different sample) the regression estimator is unbiased and no assumption is required about the relation between *Y* and *X* in the finite population.

69. If *b* is a least squares estimate, the regression estimator has a bias of order 1/*n*. However, for large samples, it has usually a lower variance than the regression estimator with pre-assigned *b*, unless there is a good a priori knowledge of the reasonable value of *b*.

70. The regression estimator with preassigned *b* is safer if unbiasedness is priority, distributions are highly skewed or *X* and *Y* have a non-linear link.

Regression estimators and stratification

71. Image classification should be performed separately in ground survey strata and in zones in which each land use has radiometric behaviour as homogeneous as possible - that means in general for each image or set of images of the same date and same instrument. A ground survey stratum not covered by a single image is split by image boundaries. Sometimes, many strata are generated by the intersection of the ground survey stratification and satellite images.

72. The use of the regression estimator suggests regrouping some strata, particularly where *b* is estimated from the sample. A sample size of thirty segments is often considered an inferior limit for large samples. This number is reasonable, or even too large, for very dominant crops, but may be not enough in a situation in which a few segments have a very strong influence on the results of the regression.

73. If the estimates of regression parameters are not very reliable, even after aggregation of several strata, the ground survey estimates and their corresponding variances should be used for the computation of the final results. This can happen for minor crops concentrated in small areas. An attempt to improve the results can be done in this case through a new specific stratification, rather than using a risky regression correction.

Cost effectiveness

74. The crucial point is the cost effectiveness of the method. The ratio between the variance of the ground survey area estimate and the variance after this estimate has been corrected with the aid of satellite images is named the relative efficiency of remote sensing. In the case of simple regression, if the sample is large enough, the efficiency is approximately $1/(1-r^2)$, where r is the linear correlation between Y_c (ground survey data) and X_c (classified image).

75. Relative efficiency of remote sensing gives a criterion for an economical evaluation of the procedure. It will be economical if the relative efficiency reaches a threshold that can be computed comparing the cost of supplementary segments in the sample and the total cost of image acquisition and analysis.

76. An analysis of the relative efficiency of remote sensing using SPOT and TM satellite sensors was performed in the frame of Regional Inventory action of the MARS project (Taylor et al. 1997). Since ground survey estimates are corrected through the regression estimator, relative

efficiencies of remote sensing are named relative efficiencies of the regression estimator. Table 5 shows the area-weighted average of the relative efficiencies for each of the main test sites.

Table 5. Area weighted relative efficiencies of the regression estimator by site and overall

	1988	1989	1990	1991
Bavaria (Germany)	1.52	1.88	4.27	*
Centre (France)	1.70	1.81	2.34	3.32
Ile-de-France (France)	*	*	3.63	3.17
Castilla-León (Spain)	1.97	2.01	1.84	1.70
Macedonia (Greece)	1.98	2.20	1.66	1.82
Emilia Romagna (Italy)	1.15	1.44	1.43	1.11
Overall	1.65	1.83	2.55	2.58/2.36

From Taylor *et al*. 1997

77.   In 1988, values of relative efficiencies, corresponding to the threshold for cost-effectiveness, were computed for each test site and satellite sensor and are presented in table 6. The figures were based on costs estimated by the contractors. The limit is when the cost of remote sensing equals the cost of increasing the size of the ground survey; thus the thresholds are influenced by variations in the cost of ground survey.

78.   A comparison of tables 5 and 6 suggests that obtained relative efficiencies are generally higher than the thresholds. The threshold values also varied with satellite sensor, due to the difference in price between SPOT and TM images.

Table 6. Threshold values of the relative efficiency of using remote sensing in 1988

	Centre	Bayern	Emilia Romagna	Macedonia	Castilla León
SPOT	1.71	1.54		2.00	1.71
TM	1.42	1.35	1.37	1.86	1.42

From Taylor et al. 1997

79.   Indeed, if the median value (instead of the weighted average of the relative efficiencies for the different crops) is considered, a different conclusion is reached.

80. Moreover, threshold values were computed from unitary costs estimated by the contractors before starting the work. In particular ground survey costs were estimated to be around 150 to 200 Ecu (today Euro) per segment of 49 ha. The cost structure changed carrying out the work in successive years, quite surprisingly, in the sense that ground survey costs decreased more than remote sensing costs. In current operational segment surveys in Europe the cost per segment is around 50 to 60 Euro and this results into much higher efficiency thresholds for cost effectiveness. Particularly, for SPOT-XS sensor, real threshold values revealed to be extremely high, due to high image cost.

81. Values for TM sensor in table 6 are very similar to the ones calculated by ITA Consortium for the operational project carried out every year in Italy (Giovacchini and Brunetti, 1992), thus, they could be considered realistic only for an optimised process.

82. Anyway, since the only problem concerning the use of the regression estimator with remote sensing data is the cost, we should consider that the cost-quality ratio of computers and satellite images is decreasing; thus, these thresholds computed ten years ago are no more valid.

83. Then, it must be taken into account that remote sensing provides more than an improvement of the statistical precision, since an information on the location of the crops, or other land uses, is also given.

Cost effectiveness for the Italian project

84. We have performed an analysis of relative efficiencies of regression in the Italian project, summarising relative efficiencies for the different administrative regions through a weighted average. Weights are given by the percentages of crop in the different regions. Net relative efficiencies have also been computed, according to the methodology described in Giovacchini and Brunetti, 1992, with two images prices, the usual price and rush service price (tab. 7). The net relative efficiency takes into consideration the price due to the use of remote sensing data. Substantially, the net relative efficiency is given by the relative efficiency multiplied by the ration between the relative cost, per sample unit, of a methodology that doesn't use remote sensing and the relative cost, per sample unit, of a methodology using the regression estimator. Thus, the correction of ground survey estimates with the regression estimator can be considered cost-effective if the net relative efficiency is higher than 1.

85. From this analysis, it appears evident that regression correction of ground survey estimates is cost-effective in the Italian project, given its own cost structure.

Table 7. Weighted efficiencies and net relative efficiencies of regression with two images prices (usual price * and rush service**), for main crops, across Italian administrative regions in 1997 and in 1998

Crops	area (ha) 1998	Rel. eff. 1997	Rel. eff. 1998	Net rel. eff. * 1997	Net rel. eff. * 1998	Net rel. eff.** 1997	Net rel. eff.** 1998
Durum wheat	1,534,708	1.44	2.39	1.17	1.94	1.08	1.79
Soft wheat	591,421	1.66	2.22	1.34	1.80	1.25	1.67
Barley	312,633	1.09	1.53	0.88	1.24	0.82	1.15
Colza	58,252	1.11	1.75	0.90	1.42	0.83	1.31
Maize	976,133	2.24	2.99	1.81	2.42	1.68	2.24
Sunflower	281,235	1.98	2.44	1.60	1.98	1.49	1.83
Soy been	431,300	2.18	2.98	1.77	2.41	1.64	2.24
Sugar beet	315,964	2.42	3.48	1.96	2.82	1.82	2.61
Tomato	90,733	3.51	2.89	2.84	2.34	2.63	2.17
Tobacco	45,077	3.93	3.15	3.18	2.55	2.95	2.36
Italy	4,637,456	1.83	2.58	1.48	2.09	1.37	1.94

86. Other studies find different conclusions: the regression correction is feasible unless the landscape is extremely fractionated, but the precision improvement of area estimates by a posteriori remote sensing is not enough to make up for the price (Allen, 1990).

87. ITA Consortium states that if the procedures of satellite data acquisition, correction, enhancement and so on are optimised and automated in an operational project, then the use of the regression estimator with remote sensing data is cost effective. Moreover the optimisation of the procedure has an influence also on the linear correlation between remote sensing data and the ground truth, which affects the efficiency of the regression estimator, as shown in table 7.

Estimators based on confusion matrixes

88. A different approach, named direct calibration estimator based on a confusion matrix, was used in Belgium in 1992 (Gallego 1994) and in an area in the "département" Indre et Loire, in France (Brun et al. 1992). In both cases, a SPOT-XS image was used. In Belgium, the ground survey was collected drawing all the fields' limits on aerial photographs, in square segments. Relative efficiencies of the direct calibration estimator were compared with the relative efficiencies of the regression estimator. The comparison didn't give clear conclusions; although the regression estimator looked a bit more efficient.

89. In France, the ground survey was based on the TER-UTI system. The land use was observed only on 36 points of a regular grid superimposed on 36 segments of 1800 m × 1800 m. This kind of ground survey created specific problems for the use of the auxiliary variables. Relative efficiencies were compared with the ones obtained with the regression estimator on the same area using 36 small segments (36 ha) completely enumerated. Relative efficiencies were almost always lower for the direct calibration estimator based on the confusion matrix than for the regression estimator.

Conclusions

90. Currently, list frames are more often used than area or multiple frames. The two approaches can give different results in different situations, depending on the aims of the projects and on the information available in a country. The assumption that list frames are more efficient than multiple frames is not always confirmed by experiences, since list frames are very sensitive to obsolescence. The consequences of the use of obsolete and incomplete lists can be serious, if a survey of the agricultural sector and not only the production of figures for main agricultural items is the aim. In fact, the largest farms generally produce the biggest amount of most commodities, but the behaviour and the economic and social conditions of the other farms are generally very different.

91. An important characteristic of the area frame component of multiple frames is their versatility, that allows to collect not only information concerning agricultural variables, but also data on environmental items.

92. When only variables concerning land use have to be estimated, estimates based on area frames don't suffer too much for instability due to outliers. Thus, the list component of a multiple frame is not essential, except for particular crops with small extension and highly concentrated in a small number of farms scattered on the territory.

93. For land use estimates, area frames based on square segments can be a good and cost effective alternative to area frames based on segments with physical boundaries, particularly where it is difficult to find many permanent physical boundaries; but non sampling errors can be more relevant. Besides, when only some points are observed on square segments, during the quality control process, it is difficult to distinguish between location and identification errors. This method can be reliable and cost-efficient only in areas with very large fields.

94. Remote sensing is very useful for the production of agricultural statistics and can be used in various ways, but should not be used as a direct tool for crop area estimation. The most well known way is in area frame construction. In fact, when area frames with permanent physical

boundaries are produced, strata and counting units are drawn on remote sensing images, through a manual or computer assisted procedure.

95. Remote sensing data are often used for stratification, in area frames with square segments as well as in area frames with permanent physical boundaries. Photo-interpretation of remote sensing images can be used to create an optimum sample design where a previous ground survey isn't performed; in fact, spatial characteristics (e.g. correlograms) of variables of interest can be estimated on the basis of photo-interpretation of remote sensing images.

96. Sometimes remote sensing data are used as auxiliary variables to improve the precision of estimates. The usual way of combining ground estimates and remote sensing is through the regression estimator, but other methods based on confusion matrices can be applied.

97. Cost-effectiveness of remote sensing is a debated question, depending on many parameters, such as the level of fragmentation of the landscape, the weather conditions, the level of optimisation and automation of the project, the cost structure and so on. Thus, different results have been reached in different experiences. Anyway, it should be considered that the cost-quality ratio of computers and satellite images is decreasing and this aspect will influence considerably the cost structure of projects devoted to crop are estimation.

98. Then, it must be taken into account that remote sensing provides more than an improvement of the statistical precision, since an information on the location of the crops, or other land uses, is also given.

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