Airborne laser scanning data as a source of field topographical characteristics

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ABSTRACT

One of the factors frequently affecting yields is topography. Topographic data can be obtained from various sources with different precision. This work evaluates suitability of airborne laser scanning data for use as another source of topographical characteristics creation in a smaller scale in regards to precision agriculture needs. Simple models of elevation, slope and flow accumulation were created and the correlation between yield and topography was determined over a seven-year period in relation to precipitations and temperature. The suitability of airborne laser scanning data was proved with certain limitations. Flow accumulation model derived from original airborne laser scanning data indicated the right trend of flow accumulation but not as clearly compared to other models. In drier years the correlation coefficients between flow accumulation and yield reached up to 60–70%.

Keywords: GIS; digital terrain models; flow accumulation; yield; weather conditions

The key element in precision agriculture is making maps that show spatial and temporal variability of yield or the factors that are important for their interpretation, such as soil characteristics, temperature and rainfall (Marques da Silva and Silva 2008). However, interpreting spatial variability in yield maps is challenging because yield is affected by many plant and soil factors and yield maps tend to vary from year to year (Guo et al. 2012).

Kravchenko and Bullock (2002) feature that topography is highly related to crop yield and topographical data are easy to obtain. Soil characteristics and terrain attributes can significantly affect water availability on hillslopes and elevation, slope and curvature have a direct effect on infiltration and runoff (Kravchenko and Bullock 2000).

The functions of the terrain can be represented using digital elevation models (DEM). The DEM is a stable factor compared to other data sources (Schmidt and Persson 2003) and its quality is dependent on a data source. The effects of topography on drainage and yields can be evaluated with methods embodied in the GIS software (Iqbal et al. 2005).

Introduction and overview of airborne laser scanning (ALS) was done by Wehr and Lohr (1999). ALS can provide data with similar height accuracy as obtained from other sources (i.e. GPS, RTK-GPS). Nowadays, modern terrain relief mapping methods have begun to be used in the Czech Republic, including airborne laser scanning.

ALS is an active remote sensing device (like radar) but Light Detection and Ranging (LiDAR) operates in the visible or in the near infrared spectrum (Hudak et al. 2002). Hodgson et al. (2003) defined electromagnetic spectra which is LiDAR working

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in the range from 1.053 to 1.064 microns. Huising et al. (1998) noted that the basic principle of ALS is measuring the distance between the scanner and the point on the surface.

ALS data are in the form of irregularly spaced point data (cloud of points), which represent a digital surface model (Straatsma and Midelkoop 2006).

Data resolution depends on the system (used pulse frequency, width of scanned territory, number of recorded reflections), on the flight height and speed and vegetation density (Thoma et al. 2005).

Vegetation density reduces the number of points reflected from the ground suitable for the creation of DTM. Kraus et al. (1998) estimated that the viability of LiDAR rays to the Earth's surface in forested areas is less than 25%. In greenwoods areas it is possible to reach higher densities of measured field points by scanning in autumn or winter period (Thoma et al. 2005). Petzold et al. (1999) noted that it is possible to scan in winter but only when there is no snow cover.

Zhang and Liu (2004) stated that the absolute accuracy of laser altimetry is up to 150 mm and relative accuracy achieved is up to 50 mm.

ALS data are a set of triplets, two horizontal and one altitude coordinates (Meyer 2007). Suarez et al. (2005) added that the data are provided in XYZ ASCII format. Nasset et al. (2002) noted that the multiple reflections (with a significant height difference) occur mainly in forests. Reflection in the meadows and cereal fields is not so much higher than a reflection from the ground.

In our previous article (Kumhálová et al. 2011a) we evaluated the suitability of elevation data from a combine harvester yield monitor for DEM, slope model (SM) and flow accumulation model (FAM) creation by a comparison with elevation data from a hand RTK-GPS. Currently, in the Czech Republic ALS data are used for digital terrain model creation and for update of basic geographic data base. The main aim of this article is therefore to evaluate the suitability of ALS data as another source for DEM, SM and FAM creation also on a smaller scale for the needs of precision agriculture.

MATERIAL AND METHODS

The experimental data for this study were obtained from experimental field of 11.5 ha in Prague-Ruzyne (50°05'N, 14°18'E), Czech Republic with a Haplic Luvisol soil. Crop rotation in observed years is indicated in Table 1. Conventional arable soil tillage technology was used on this field. Yield has been measured since 2003 with the exception of 2009 (combine harvester electrical equipment technical problems). Detailed description of yield measuring device can be found in our previous article (Kumhálová et al. 2011a). Experimental variograms of yield were computed using common procedures.

Total monthly precipitation and temperature data were provided by the Agrometeorology station at the Crop Research Institute in Prague-Ruzyne.

Table 1. Precipitations and temperatures in different growth stages by BBCH scale recorded on the experimental field over 7 years

	2005 winter wheat	2006 oat	2007 winter barley	2008 winter rape	2010 oat	2011 winter wheat	2012 winter rape
Precipitation (mm)							
BBCH 20–29	83.4	111.4	122.4	105.3	93.4	104.4	167.8
BBCH 30–49	90.4	48.6	2.4	112.6	84.7	39.5	54.1
After BBCH 89	207.8	94.6	146.6	99.6	142.3	257.4	258.9
Sum	381.6	254.6	271.4	317.5	320.4	401.3	480.8
Mean	127.2	84.9	90.5	105.8	106.8	133.8	160.3
Temperature (°C)							
BBCH 20–29	4.0	14.1	6.9	5.3	12.3	3.4	4.3
BBCH 30–49	13.9	16.6	12.8	11.8	16.5	14.8	9.5
After BBCH 89	18.4	22.2	18.1	18.9	21.1	17.9	17.8
Mean	12.1	17.6	12.6	11.9	16.6	12.0	10.5

Precipitation and temperature for observed years are also stated in Table 1.

The topographic data were obtained by using a hand-held RTK-GPS receiver and with a help of airborne laser scanning. RTK-GPS elevation data were recorded as accurately as possible (± 0.2 m) at 300 positions in the experimental field on almost regular grid. Elevation data were then interpolated by inverse distance weighting (IDW) squared (ArcGIS 10) to create the DEM. The FAM was then derived from the DEM and SM.

ALS data were kindly provided by COSMC (Czech office for surveying, mapping and cadastre) in the shape of two squares with the size of 2 × 2 km. The area that corresponded with observed field was cut from the provided data. Those data were then modified into three files. First file (original data set) obtained all 317 303 points from the observed field. Next two files of elevation data were calculated with a help of buffer procedure from ArcGIS from original ALS data set as an average from a circular area with the radius 6 m (ALS 6) and 12 m (ALS 12) relative to the same 300 points on which RTK-GPS data were recorded. DEM, SM and FAM were created from these four data sets. Thus created models were then compared with yield maps from the observed years taking into account the weather conditions in given years using geostatistical methods. The results of correlation analysis among the variables were evaluated statistically by forward stepwise linear regression. This procedure was also described in detail in previous article (Kumhálová et al. 2011a) and ArcGIS software (ESRI 2006) was used.

Forward stepwise linear regression on significance level $P = 0.05$ was used in order to evaluate an influence of topography on yield. Data analysis was done with Statistica 8.0 (StatSoft Inc., Tulsa, USA) and ArcGIS 10 (ESRI, Redlands, USA).

RESULTS AND DISCUSSION

Summary statistics procedure was applied to RTK-GPS and ALS initial data sets (Table 2). The two sets of elevation data were compared with a *t*-test to determine whether they are significantly different. It was proved that there is neither statistically significant difference between the means ($mean_{ALS}$: 345.35, $mean_{RTK\text{-}GPS}$: 345.14, *t*-test: 0.695, *df*: 317601, calc. *P*: 0.985) nor between the variances of the data derived from ALS and from RTK-GPS (SD_{ALS}: 5.132, $SD_{RTK\text{-}GPS}$: 5.185, *F*-test: 0.98, calc. *P*: 0.39) at the $P = 0.05$ significant level.

Because of sloppy terrain, spatial autocorrelation of data was tested by the Moran's Index (ArcGIS 10).

Table 2. Summary statistics, variogram model parameters and the methods of interpolation used for elevation (m) and yield (t/ha) in the experimental field

	Elevation		Yield						
	RTK-GPS	ALS	2005	2006	2007	2008	2010	2011	2012
Count	300.0	317303	8236.0	8822.0	8808.0	8440.0	9024	7548	9389
Mean	345.1	345.3	6.081	4.219	5.618	2.734	2.254	7.053	2.809
Median	344.9	344.9	6.318	4.287	5.481	2.527	2.354	7.218	2.942
Mode	353.0	337.7	6.485	4.973	5.061	0.677	2.9	5.646	2.626
Sample variance	26.88	18.99	1.308	0.909	1.885	7.283	4.724	12.869	6.623
Standard deviation	5.185	5.132	1.143	0.953	1.373	1.477	0.852	1.953	1.199
Minimum	337.3	337.4	2.075	0.989	1.109	0.059	0.101	0.589	0.100
Maximum	355.0	356.4	9.929	7.224	10.149	7.342	4.825	13.458	6.623
Skewness	0.144	0.256	–0.806	–0.515	0.015	0.126	–0.359	–0.141	–0.252
Method of estimation	–	–	method of moments						
Variogram model	–	–	exponential						
Nugget variance	–	–	0.215	0.211	0.317	1.110	0.222	1.315	0.528
Sill variance	–	–	1.285	0.655	1.010	1.419	0.428	3.479	1.198
Method of interpolation	IDW	IDW	Kriging	Kriging	Kriging	Kriging	Kriging	Kriging	Kriging

RTK-GPS – real time kinematic GPS; ALS – airborne laser scanning; IDW – inverse distance weighting

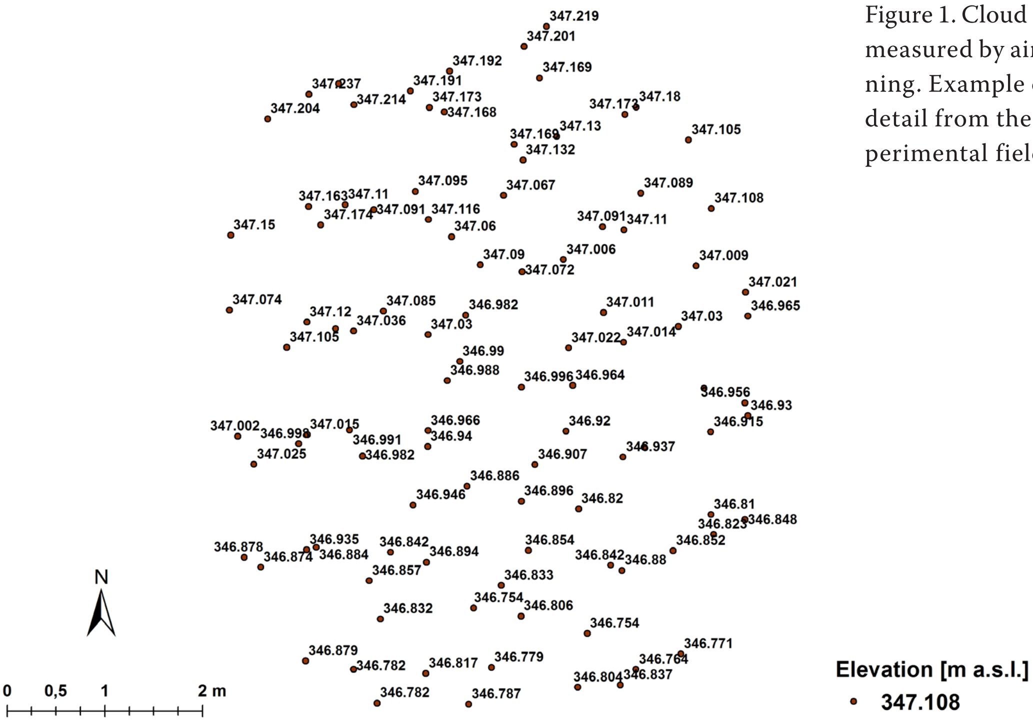

Figure 1. Cloud of elevation points measured by airborne laser scanning. Example of random square detail from the middle of the experimental field

Resulted z-score was –5.48 from this result it is obvious that there is a significant spatial autocorrelation between these two data sets and pattern expressed is dispersed.

Root mean square error (RMSE) and linear regression between RTK-GPS and ALS 6 data were also calculated to compare both data sets. Resulted RMSE value was 0.054 m which is near to zero and resulting formula of linear regression was $y = 1.001x - 0.142$ with coefficient of determination $R^2 = 0.99$. It follows from all analyses that observed data sets were quite similar.

Figure 1 shows the cloud of elevation points measured by ALS on the example of random square detail from the middle of experimental field. The distance between neighbouring points is in most cases smaller than 1 m. Southerly aspect of the experimental field is evident from ALS data even from this small cut of the field.

DEM was then created from all four observed data sets (Figure 2). All created DEM resulted very similarly. Small difference between DEM created from original ALS data set and DEMs created from ALS 6 and ALS 12 is caused by averaging of original ALS data and by number of the data in each set.

SM based on the interpolated elevation data were created with the surface analysis-slope tool (Figure 3). Some similarity can be seen especially between SM derived from RTK-GPS data and ALS 6 data. SM derived from original ALS data is most different from all three others. It is caused again by high number of ALS elevation points. From this reason the SM is derived from ALS very detailed (will be discussed later).

Figure 4 shows FAM with the flow lines derived from SM of observed data sets. To derive FAM directly from original ALS (more than 300 000 points) is a challenge. In this case the FAM is so detailed that it is not possible to clearly express flow accumulation or water flow direction trend. That is why it was necessary to reclassify slope model to nine categories and then to derive FAM from so reclassified model. FAM could then be compared with the yield and its visualization is comfortable (Figure 4b).

Minimal difference can be seen between FAM derived from RTK-GPS, ALS 6 and ALS 12. All models are able to identify the areas with a possible flow accumulation. FAM derived from reclassified original ALS data do not show those areas as clearly in comparison with three FAMs discussed above although the right trend is also indicated.

Maps of kriged predictions of yield are shown in Figure 5. It can be seen from Table 1 that the year 2005 was average from precipitations point of view. Winter wheat had probably enough of water in all important phenological growth stages (Table 1) especially in stage BBCH 30–39. Important influence of terrain relief was not observed. It was confirmed also by coefficients of determination

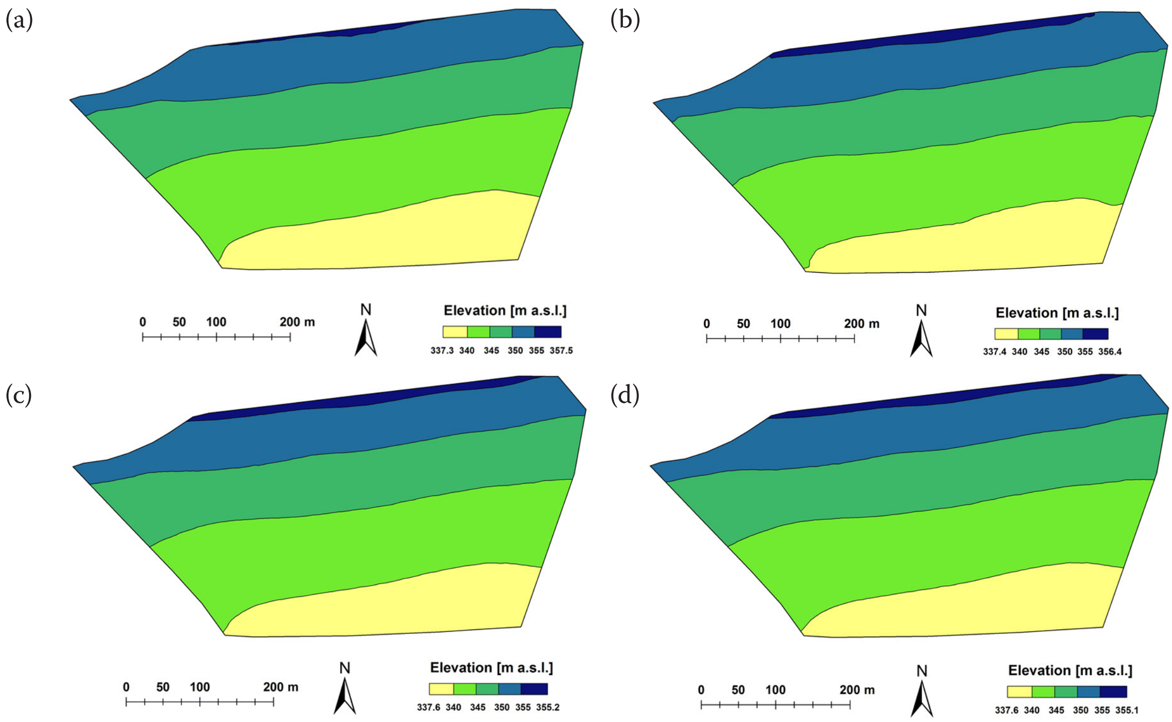

Figure 2. Maps of inverse distance weighting (IDW) interpolation of elevation (m) in the experimental field for: RTK-GPS data (a); original airborne laser scanning (ALS) data (b); ALS data set as an average from a circular area with the radius 6 m (c); ALS data set as an average from a circular area with the radius 12 m (d)

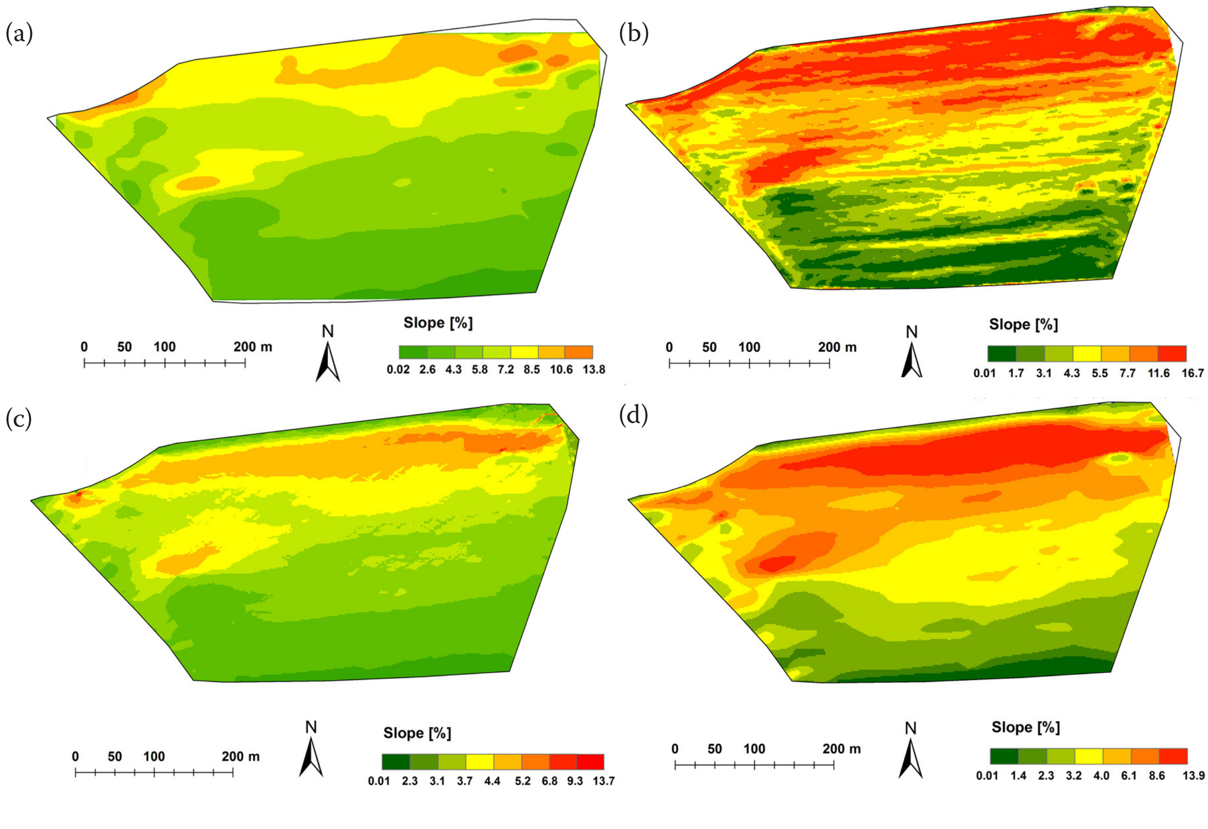

Figure 3. Maps of inverse distance weighting (IDW) interpolation of slope in the experimental field for: RTK-GPS data (a); original airborne laser scanning (ALS) data (b); ALS data set as an average from a circular area with the radius 6 m (c); ALS data set as an average from a circular area with the radius 12 m (d)

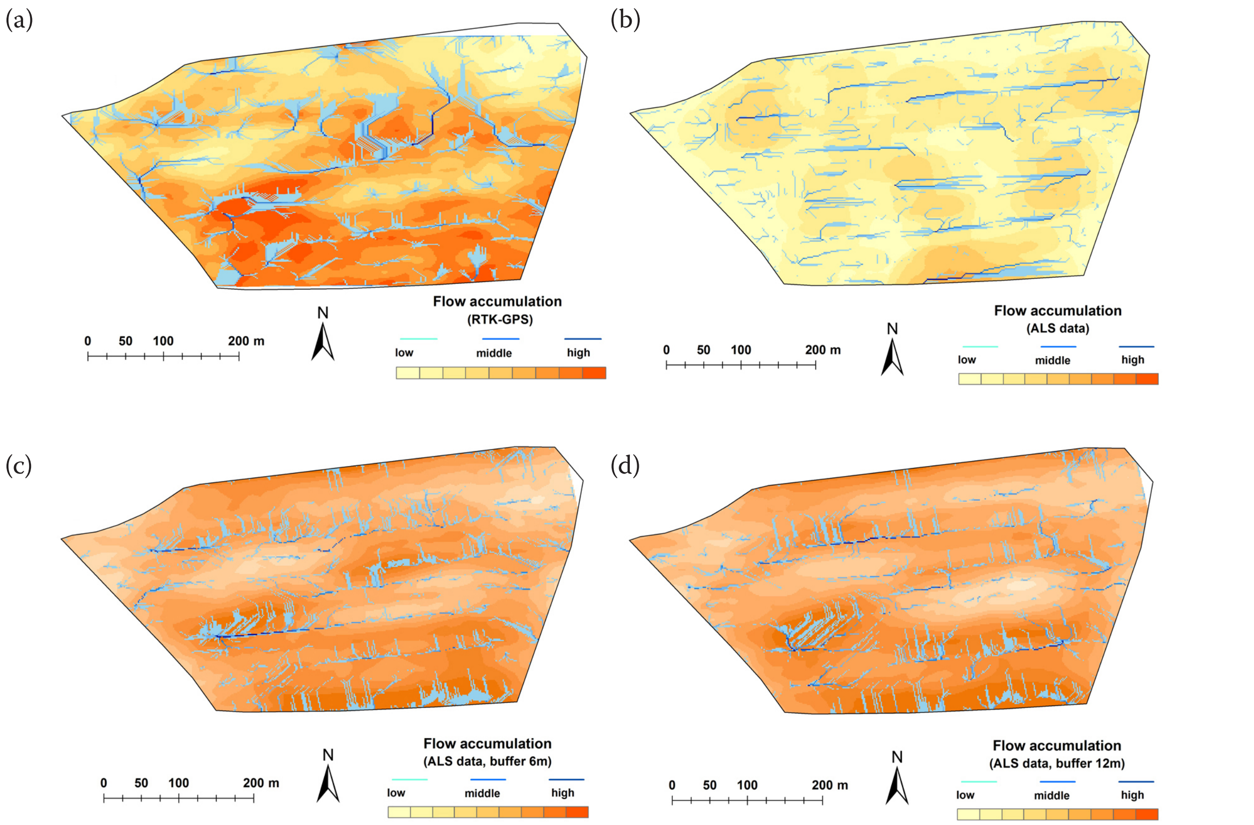

Figure 4. Maps of experimental field with flow accumulation superimposed from: elevation derived from RTK-GPS data (300 data) (a); elevation derived from original airborne laser scanning (ALS) data (317 303 data) after reclassifying to nine categories (b); elevation derived from ALS data as an average from a circular area with the radius 6 m (c); elevation derived from ALS data as an average from a circular area with the radius 12 m (d)

showed in Table 3 which were the smallest from all observed years.

Oat was grown during the driest year, 2006. Resulted coefficients of determination from FSLR were R^2 = 15.7% in the case of RTK-GPS data and R^2 = 21.9–26.7% for ALS data. These coefficients were surprisingly quite low. It can be explained by a low level of precipitations in shooting stage – only 48.6 mm during BBCH stages 30–39 (Table 1). It could cause a lower overall yield across the experimental field. Topography played a more important role in the areas with higher water concentration compared to those with smaller as it can be seen in Figure 5b. Slope of the experimental field and consequently derived FAM played here probably a significant influence as it is obvious from calculated coefficients of correlation between FAM and yield (r = 0.337 in the case of RTK-GPS data and r = 0.303–0.349 in the case of ALS data, Table 3).

The second driest year from all the monitored ones was year 2007 when winter barley was grown. Insufficient water availability during BBCH 30–39 shooting stages (2.4 mm only, Table 1) probably caused drying of the crop during growth. At least it was clear also in the areas on the field with water accumulation as can be seen from Figure 5c. Coefficients of determination calculated from FSLR resulted similarly for all observed variants. Great influence of field topography on yield was clearly demonstrated in this year.

Winter rape was grown in the year 2008 when total precipitations were in average and temperature was the second coldest from the observed years. This year was good for plant mass production in autumnal period. Rape plants grew too large for winter. This consequently caused high infestation by fungal diseases (Kumhálová et al. 2011b), which significantly affected the yield in the areas with water accumulation in our field. It can be seen also from yield map on Figure 5d. All coefficients derived from RTK-GPS data are in good agreement with this idea. Coefficient of determination resulted from FSLR was low in this case (R^2 = 12.4%). Negative correlation coefficient

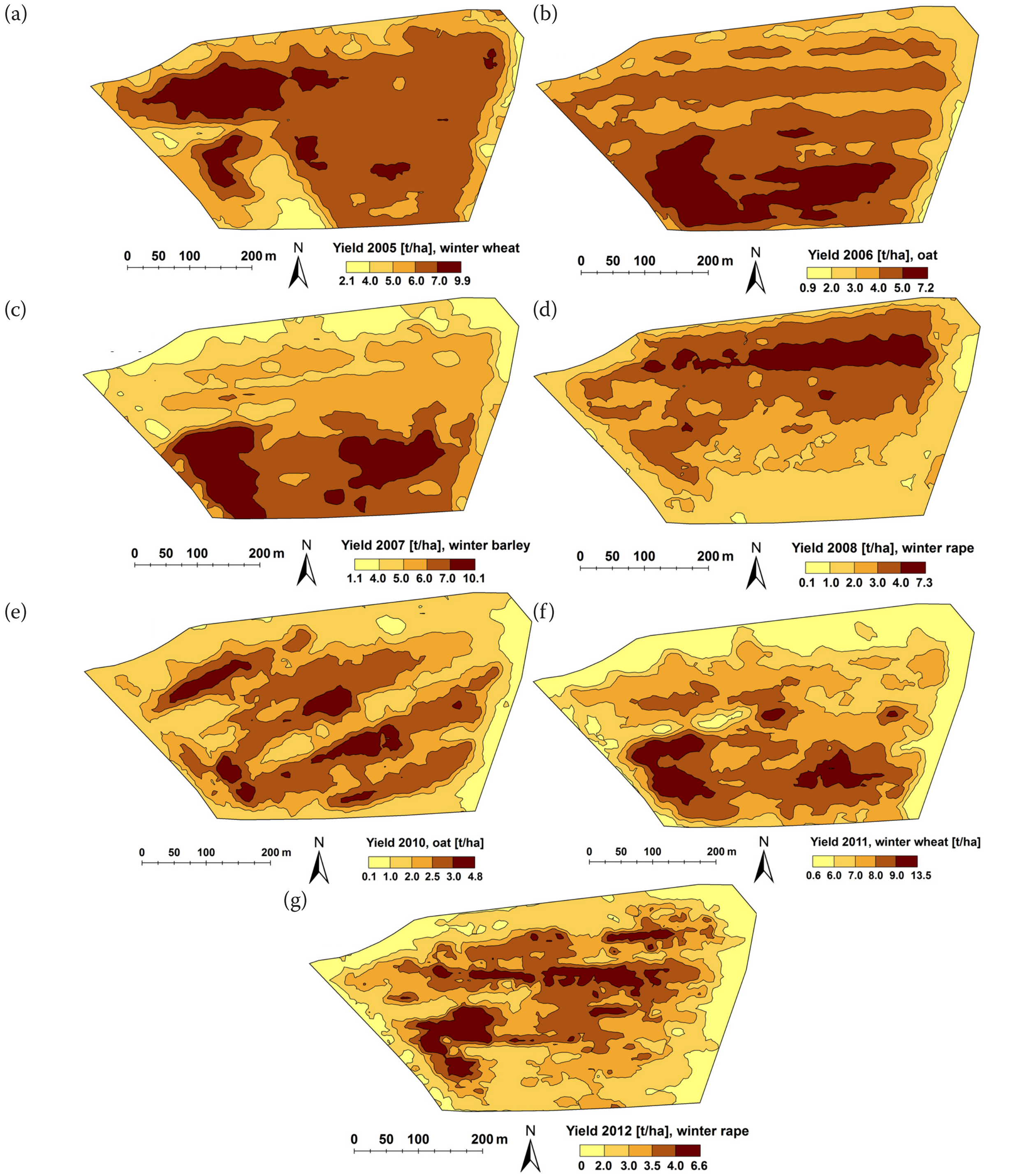

Figure 5. Maps of kriged predictions of yield in the experimental field during the observed years: 2005 – winter wheat (a); 2006 – oat (b); 2007 – winter barley (c); 2008 – winter rape (d); 2010 – oat (e); 2011 – winter wheat (f); 2012 – winter rape (g)

between yield and FAM ($r = -0.077$) was found. This coefficient resulted positive in all other observed cases. Field terrain probably had a negative effect on yield due to positive effect on plant diseases development. Nevertheless the results from ALS data did not comply with the results described above. Coefficient R^2 calculated from original ALS data resulted relatively high, 30.8% and those calculated from averaged ALS data even higher (45.8% and 52.7%). On the contrary, correlation coefficients between yield and FAM decreased with averaging of ALS data from $r = 0.258$ to 0.101.

Table 3. Correlation coefficients of the yield and topographic attributes (elevation, slope and flow accumulation) for the years 2005–2012. All coefficients are significant at 5% significance level. Coefficients of determination (R^2) between yield and topographic attributes resulting from forward stepwise linear regression (FSLR)

		Elevation data derived from RTK-GPS			Elevation data derived from ALS			Elevation data derived from ALS 6			Elevation data derived from ALS 12		
		DEM	SM	FAM	DEM	SM	FAM	DEM	SM	FAM	DEM	SM	FAM
2005	yield	–0.051	–0.007	0.049	–0.044	0.121	0.478	–0.044	0.244	0.181	–0.046	0.286	0.179
	FSLR	R^2 = 1.4%			R^2 = 24.7%			R^2 = 14.7%			R^2 = 19.9%		
2006	yield	–0.334	–0.241	0.337	–0.398	–0.241	0.303	–0.402	–0.106	0.319	–0.404	–0.084	0.349
	FSLR	R^2 = 15.7%			R^2 = 21.9%			R^2 = 23.4%			R^2 = 26.7%		
2007	yield	–0.734	–0.583	0.586	–0.790	–0.482	0.241	–0.791	–0.341	0.373	–0.791	–0.343	0.411
	FSLR	R^2 = 59.8%			R^2 = 64.8%			R^2 = 66.9%			R^2 =68.7%		
2008	yield	0.281	0.333	–0.077	0.323	0.488	0.258	0.327	0.592	0.174	0.330	0.661	0.101
	FSLR	R^2 = 12.4%			R^2 = 30.8%			R^2 = 45.8%			R^2 = 52.7%		
2010	yield	–0.190	–0.069	0.277	–0.232	–0.077	0.367	–0.236	0.037	0.327	–0.238	0.085	0.323
	FSLR	R^2 = 12.2%			R^2 = 17.1%			R^2 = 18.2%			R^2 = 22.3%		
2011	Yield	–0.425	–0.307	0.393	–0.437	–0.183	0.418	–0.439	–0.045	0.470	–0.439	–0.004	0.497
	FSLR	R^2 = 23.5%			R^2 = 32.9%			R^2 = 39.9%			R^2 = 47.0%		
2012	yield	–0.225	–0.138	0.229	–0.156	0.066	0.365	–0.154	0.200	0.288	–0.155	0.257	0.250
	FSLR	R^2 = 8.3%			R^2 = 18.1%			R^2 = 22.6%			R^2 = 28.3%		

DEM – digital elevation model; SM – slope model; FAM – flow accumulation model

This fact deserves further attention and will be discussed in some of forthcoming articles.

In 2010 oat was grown again. As a result of rainy weather (between stages BBCH 71–99), oat vegetation flattened before the harvest which caused serious problems. It was necessary to adjust direction of combine harvester working travels according to oat flattening. This fact can be seen also from yield map (Figure 5e), which is quite different from the other ones. Although yield map was deformed, the results from FSLR are quite logical. No significant dependence of the yield on observed parameters was found in any of the cases.

The precipitation was different in year 2011 (winter wheat). Dry period during flowering (BBCH 61–69) caused that the influence of flow accumulation was evident (FAM derived from RTK-GPS: $r = 0.393$; FAM derived from ALS: $r = 0.418–0.497$). The main difference between wheat yield maps from 2005 and 2011 can be seen especially on headlands. Kroulík et al. (2010) measured draft force in experimental field. Compacted soil in headlands was found. In 2005 the influence of compacted soil in headlands of the field was not so evident (relatively wet spring). In 2011 the influence of soil compaction in headlands was probably higher (relatively dry spring). Soil compaction on headlands also increased during observed years quite likely because of field cultivation by relatively heavy machinery. It could be the cause of poor plants root system creation and consequently lower yield in these areas of field (Figure 5f). Moreover, this effect can be observable just in previous years.

The coldest and richest in precipitation was year 2012 (winter rape). This weather course probably caused that rape crop was well during autumn period (especially in stages BBCH 10–19). Nevertheless, the worst uptake of nitrogen fertilization on drier places of the field was probably caused by relatively low precipitations during flowering (BBCH 60–69). The influence of topography can be seen in south-western part of the field as usually in Figure 5g. The influence of soil compaction on headlands is also obvious.

On the basis of the presented results it can be concluded that ALS data can be used as a source for DEM, SM and FAM modelling using commonly used GIS software packages. Problems might cause relatively large amount of original ALS data. Topography and weather conditions affected the yield in our field. The relation between yield and topography was more important in dry years. In wet years topography can also influence fungal diseases development.

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