SEEING THE RIGHT MOMENT FOR SILAGE HARVEST: METHODS AND DECISION FRAMEWORKS

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Abstract

Finding the right time for maize silage harvest is one of the biggest practical challenges in forage production. Farmers must balance feed quality, yield, weather, and harvest logistics often within only a few days. In reality, harvest decisions are still mostly based on field experience and limited sampling, even though crop maturity can vary considerably within the same field

This paper presents a practical framework combining multispectral drone monitoring, laboratory analysis, and field observations to support harvest decisions under real farming conditions. The approach was tested on multiple maize hybrids and agronomic treatments, with monitoring from standing crop through harvest to final silage.

Part of the experiment was affected by unfavorable weather during harvest, which revealed the difference between theoretical prediction and practical farming reality. The results show that UAV monitoring can become a useful tool for silage management, especially when combined with agronomic experience and laboratory validation.

Keywords: maize silage, Earth Observation, UAV monitoring, dry matter, field heterogeneity, harvest timing

INTRODUCTION

In practice, the decision is rarely straightforward. Farmers must balance crop maturity, expected feed quality, weather uncertainty, field accessibility, and harvest logistics within a very limited time window. Harvest timing is therefore often based on field experience, visual crop assessment, calendar estimates, and limited laboratory sampling.

Months to Grow, Days to Harvest, Months to Feed

This imbalance between the length of crop production, the very short harvest window, and the long feeding period creates significant pressure on decision-making. Maize is cultivated for several months, harvested within approximately one to two weeks, and then used in cattle feeding for many additional months. The final harvest decision therefore represents an economic and organizational compromise under time pressure. Responsibilities on modern farms are often divided between agronomists, harvest contractors, nutrition specialists, and farm management, each working with different priorities and budgets. While the agronomist focuses on crop condition and yield, harvest logistics are constrained by machinery‘s availability and operational costs, and nutritionists evaluate the long-term impact on feed quality and animal performance. The overall farm profit is often distributed across separate operational budgets and therefore not immediately visible, as illustrated in Figure 1.

One Field, Multiple Crop Conditions

In reality, maize fields are rarely uniform. Different parts of the same field may develop differently due to soil conditions, water availability, hybrid characteristics, local stress factors, or previous agronomic interventions. Variability within the field often becomes even more visible during dry periods or under unstable weather conditions. As a result, point sampling can only describe a small portion of the field and may not fully reflect the actual crop condition across the entire harvested area. For practical harvest management, this creates a gap between laboratory precision and the spatial reality of the field.

The Hidden Cost of Silage Losses

An 18% silage loss may represent:

- approximately 100,000 EUR in additional silage purchase costs or
- around 130,000 EUR in unrealized electricity revenue from biogas production compared with a well-preserved silage loss of 5% (2,889 t × 35 EUR/t silage; 2,889 t × 343 kWh/t × 0.13 EUR/kWh) or
- approximately 1 500 000 EUR in potential milk production value (2,889 t × 1,300 l milk/t silage × 0.40 EUR/l milk).

These estimates are based on simplified calculation models and average market values. An actual economic impact depends on multiple factors including silage quality, digestibility, starch content, animal performance, storage conditions and energy conversion efficiency.

Monitoring the Reality of the Field

Understanding the crop variability under practical farming conditions requires more than a single field visit or a laboratory measurement. In this study, the UAV monitoring,

Fig. 1: A silage bunker at a biogas plant in South Moravia, the Czech Republic (2025, 2024). Comparison of silage preserved with and without the use of a preservative in consecutive years under practical farm conditions, illustrating the contrast between short-term agronomic cost reduction and long-term biomass utilization efficiency. The recorded biomass loss reached approximately 18%.

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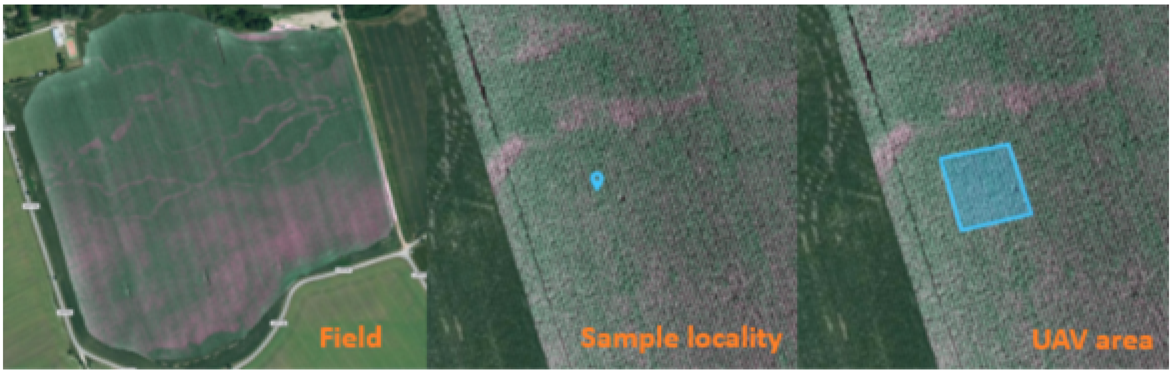

Fig. 2: Maize field in the Slovácko region, the Czech Republic (2024). UAV monitoring revealed differences in crop maturity and dry matter content across the field. Higher dry matter values were observed near the road, while the opposite side, inaccessible by car, remained at the milk stage of maturity. Laboratory analysis showed 27.52% DM compared with 30.34% estimated from UAV.

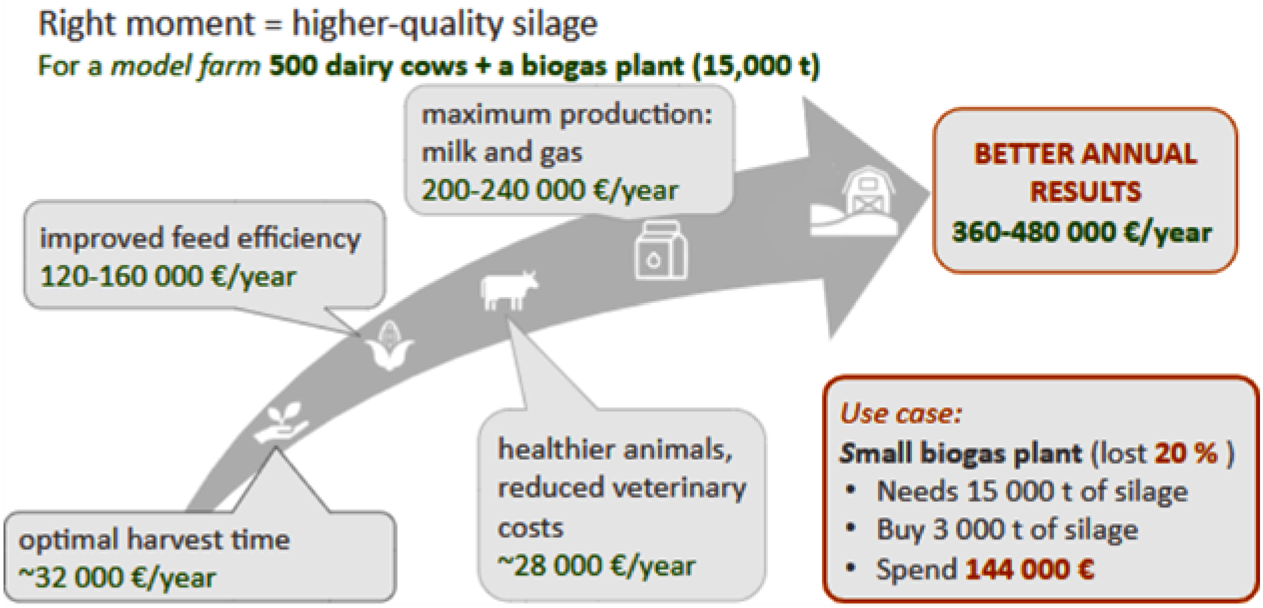

Fig. 3: Influence of individual operational budgets on the overall economic performance of dairy and biogas production under practical farm conditions

the laboratory analyses, and the field observations were combined throughout the vegetation period to capture the changes in crop maturity, dry matter development, and spatial variability across the field. Particular attention was given to the differences between the maize hybrids, the agronomic treatments, and the areas exposed to different water availability and stress conditions. The monitoring continued from the standing crop through the harvest and the final silage production, allowing the comparison of the theoretical predictions with the practical reality observed during the harvest and conservation process.

MATERIALS AND METHODS

The objective of this study was not to evaluate a single sensing technology under controlled experimental conditions, but to compare the practical role, limitations, and decision-making value of different methods currently used for silage harvest management. The presented approach therefore focuses on the integration of multiple information sources under real farming conditions rather than on the development of a specific predictive model.

Modern silage management increasingly combines multiple sources of information, each providing a different perspective on crop development and harvest readiness (Figure 4). Satellite monitoring is commonly used for large-scale observation of vegetation development during the season, while UAV monitoring enables a more detailed evaluation of spatial variability within individual fields. During harvest, onboard NIR sensors provide rapid real-time estimation of crop parameters directly on the harvester. Laboratory analyses remain the reference method for determining dry matter and nutritional quality, although they are limited by sampling frequency and processing time.

The practical challenge is no longer the availability of individual technologies, but the integration of these data sources into a single decision framework capable of supporting practical harvest decisions under real farming conditions. Particular attention was therefore given to how individual methods contribute to decision-making under conditions of crop variability, weather uncertainty, operational constraints, and differing economic priorities within the farm management system.

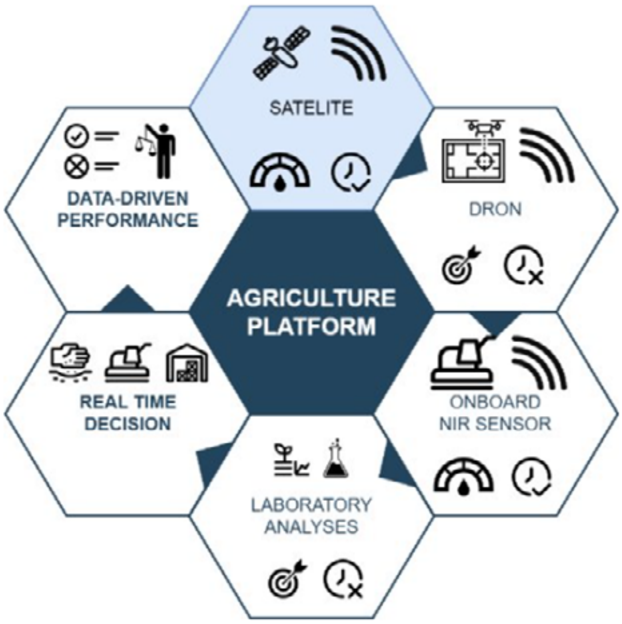

Fig. 4: Overview of the main data sources used for harvest decision support, combining satellite monitoring, UAV sensing, onboard NIR measurements, laboratory analyses, and real-time operational data into a unified agricultural decision framework.

Seeing Crop Development Over Time

One of the major advantages of modern remote sensing methods is their ability to monitor crop development repeatedly throughout the growing season without destroying the measured material. Both satellite and UAV monitoring are based on the principle of non-destructive sensing, where reflected electromagnetic radiation from the crop canopy is used to estimate vegetation condition, crop development, and spatial variability within the field.

Satellite monitoring provides a continuous large-scale overview of vegetation development during the season and allows the observation of long-term trends across extensive agricultural areas. Its main advantage lies in regular revisit times and the ability to monitor crop dynamics over time. However, the spatial resolution and cloud sensitivity may limit the detailed evaluation of variability during critical harvest periods. Another practical limitation is that publicly available satellite imagery is typically accessible with a delay of approximately one day after acquisition, reducing its suitability for immediate operational decisions during rapidly changing harvest conditions.

UAV monitoring enables a flexible and spatially detailed assessment of crop conditions directly before harvest. Multispectral UAV sensing allows the detection of within-field variability, including differences in crop maturity, stress conditions, and dry matter development. By providing high-resolution observations focused on specific fields and operational decision-making, UAV monitoring effectively complements satellite data.

Both technologies were considered complementary rather than competing approaches. Satellite monitoring provides continuous seasonal context, while UAV monitoring delivers detailed local information during critical decision periods. Together, they create a more synchronized view of crop development, combining long-term monitoring with field-scale operational evaluation under practical farming conditions.

Seeing Quality During Harvest

Both laboratory analyses and onboard NIR sensing aim to evaluate the nutritional and technological quality of the harvested crop. Their common objective is to estimate key parameters influencing silage preservation, feed quality, and harvest timing, particularly dry matter content.

Laboratory analyses remain the reference method due to their high analytical precision and the possibility of evaluating a wide range of nutritional parameters. However, the results are limited by sampling frequency, processing time, and the representativeness of the collected sample. Under rapidly changing harvest conditions, the analytical result may no longer fully reflect the actual field situation at the moment of harvest.

Onboard NIR sensing enables continuous real-time monitoring of crop quality parameters directly during harvesting, allowing the preservation of information about the harvested material flow without extensive manual sampling. However, NIR measurements are still based on calibration models and linear regression approaches and therefore represent operational indicators rather than absolute analytical values. While onboard sensing can reliably identify trends, variability, and minimum or maximum zones during harvest, laboratory analyses may still reveal a wider variability range and higher analytical precision within the harvested material.

Both methods were considered complementary rather than competing approaches. Laboratory analyses provide reference validation and nutritional interpretation, while onboard NIR sensing enables continuous monitoring of quality changes during harvest under practical farming conditions.

Fighting Drought: Practical Field Observations

Drought stress has become one of the major challenges influencing maize production and harvest stability under practical farming conditions. By combining Earth Observation methods with conventional laboratory analyses, it became possible to work with field heterogeneity in a way that is difficult to achieve using traditional point-based sampling alone. The following practical observations demonstrate how spatial monitoring introduced an additional perspective into the interpretation of otherwise conventional agronomic and laboratory data.

Hybrid Influence on Field Heterogeneity was evaluated under foothill conditions using eight maize hybrids intended for future field deployment. The objective was to compare hybrid behaviour under uneven water availability and to estimate their potential contribution to milk production. All nutritional parameters were determined from samples consisting of five consecutive maize plants, with grain and green biomass evaluated separately. Particular attention was given to spatial variability detected through Earth Observation methods, which revealed differences in crop development and field heterogeneity that were not fully visible during standard field inspections and conventional laboratory evaluation.

Hydrogel Application and Crop Development and field variability was evaluated under identical field conditions using the same maize hybrid and locality. The monitored treatment consisted of four rows with hydrogel applied beneath the seed together with fertilizer, compared with four control rows receiving fertilizer only. All nutritional parameters were determined from samples consisting of five consecutive maize plants, with grain and green biomass evaluated separately. Earth Observation methods were used to monitor the spatial development of the crop and to evaluate differences between the treated and untreated variants during the vegetation period.

RESULTS AND DISCUSSION

While the presented experiments demonstrated the practical value of combining laboratory analyses, Earth Observation methods, and onboard sensing, they also revealed several important limitations affecting harvest decision-making under real farming conditions. Field heterogeneity, rapidly changing weather conditions, sampling strategy, and the loss of spatial context during harvest may significantly influence the interpretation of otherwise accurate analytical data. In several situations, individual methods provided results that appeared technically correct but did not fully describe the actual biological and operational complexity of the crop. These observations highlighted that the practical challenge is often not the absence of data, but rather the correct interpretation of information obtained from different sources, scales, and time horizons. The following practical cases illustrate several situations where conventional interpretation approaches may lead to misleading conclusions if the broader spatial and agronomic context is not considered.

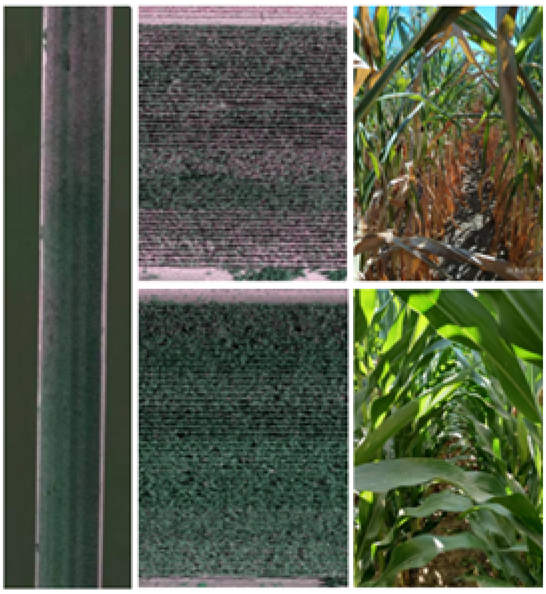

Fig. 5: Selection of maize hybrids in the foothill region of the Orlické Mountains, the Czech Republic (2024). Captured by UAV

Hybrid Influence on Field Heterogeneity

The experiment was located on a strongly heterogeneous field, where the influence of drought significantly affected the validity and interpretation of the trial. While the front part of the field (sampled) remained in relatively good condition, the rear part showed severe drought stress and partial crop desiccation.

Earth Observation monitoring revealed visible differences in crop maturity and canopy development between the evaluated hybrids. Individual hybrids were distinguishable not only through multispectral monitoring, but also by direct visual observation in the field, with each hybrid showing a different response to water stress and maturity development. Laboratory analyses indicated grain starch content ranging from 60 to 72%, green biomass dry matter from 30 to 36.5%, grain dry matter around 63.5%

Hydrogel Application and Crop Development

During the dry period in June and July, the hydrogel variants showed visibly stronger crop development and greater canopy stability.

However, wetter conditions during August and September reduced the visible differences before harvesting, and UAV monitoring no longer detected substantial heterogeneity between the variants. Despite the visually compact crop canopy, laboratory analyses revealed heavier and more developed cobs in the hydrogel-treated variants. Although the differences were not statistically significant due to field variability, the results indicated an approximately 5% higher yield potential.

Onboard NIRS sensing did not detect significant differences during harvest, while the final weighing of the harvested biomass confirmed an approximately 5% increase in yield in the hydrogel variants. Detailed UAV analysis is summarized in Table 1.

Practical Case of Failure

Precision without representativeness may lead to misleading harvest decisions even when laboratory analyses themselves are analytically correct. In one practical case, the agronomist regularly delivered a single maize plant to the laboratory every three days for precise dry matter determination. Although the analytical accuracy was high, the measured values fluctuated significantly over time due to natural field variability and inconsistent sample selection.

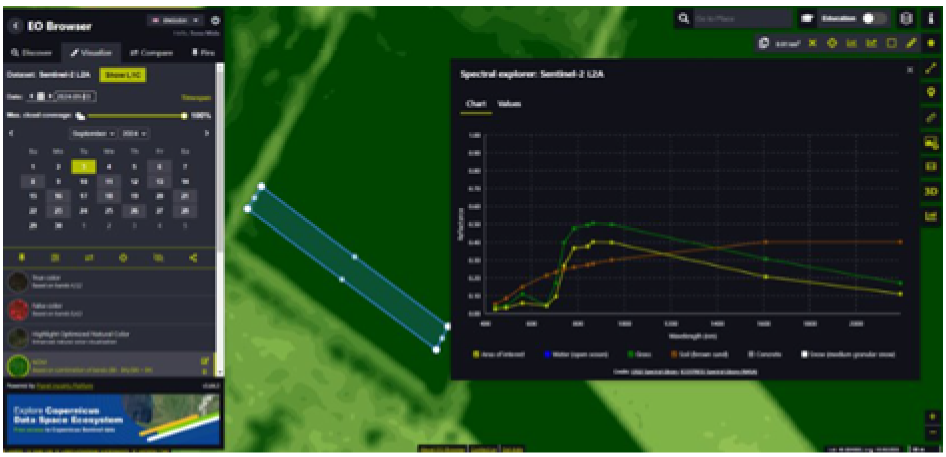

Fig. 6: Selection of maize hybrids in the foothill region of the Orlické Mountains, the Czech Republic (2024). Captured by Copernicus

Tab. 1: Comparison of UAV-derived dry matter parameters between maize variants with and without hydrogel application under practical field conditions.

UAV Parameters	Without hydrogel					With hydrogel				
	H1	H2	H3	H4	Avg.	H1	H2	H3	H4	Avg.
Avg Field DM (%)	34.4	37.5	32.0	32.0	34.0	36.0	33.2	32.1	31.9	33.3
Biomass DM (%)	35.0	37.4	31.7	31.5	33.9	35.8	32.8	31.6	31.2	31.5
Optimal Area (%)	**53.3**	**64.4**	**58.9**	**65.2**	**60.4**	**72.9**	**73.2**	**62.1**	**63.2**	**67.9**
Veg. Coverage (%)	99.1	99.5	100	100	99.6	100	100	100	99.8	99.9

This case illustrates that harvest decision-making cannot rely only on analytical precision if the sampling strategy itself remains random or operationally biased. Integrating Earth Observation data into the sampling process allows the identification of representative field zones and supports a more transparent and spatially informed selection of laboratory samples before harvest decisions are made.

False positives in Earth Observation may occur when crop spectral response no longer fully reflects the actual harvestable biomass condition. UAV-based monitoring can show very good predictive performance in well-developed and spatially uniform stands. However, in mountainous regions where maize reaches physiological maturity but produces limited biomass, remote sensing may falsely indicate harvest readiness despite insufficient silage yield.

A similar situation may occur during extremely dry weather conditions, when leaf senescence rapidly changes the spectral response of the canopy, while the stalk and cob still retain significant moisture. In such cases, remote sensing may indicate advanced maturity even though the actual dry matter development of the harvestable biomass remains incomplete.

These situations illustrate that Earth Observation methods should not be interpreted as isolated indicators, but rather as decision-support tools requiring agronomic context, field observations, and validation through complementary measurements.

Homogenization of harvested material is beneficial for silage stability and feed consistency, but it may simultaneously reduce the ability to evaluate the real performance and variability of individual field zones. During harvest, onboard NIR sensing continuously measures crop quality parameters across the harvested material flow. However, once the material becomes mixed during transport and storage, the direct connection between measured values and their original field location may be partially lost.

Uniform onboard harvest data do not necessarily guarantee uniform silage behavior during storage and feed-out. In practical conditions, NIR records from multiple fields may show similar dry matter values, for example within a range of 32–38 % with an average around 36 %, suggesting apparently homogeneous harvest quality. However, Earth Observation data may simultaneously reveal pronounced spatial differences in water availability, crop stress, and field moisture conditions.

These hidden differences can later influence fermentation dynamics and aerobic stability, even when the harvested material appears analytically similar during collection. Dry and stressed zones may behave differently during ensiling than wetter and physiologically active parts of the field, despite comparable average dry matter values.

CONCLUSION

The presented observations demonstrate that practical silage harvest decisions cannot rely on a single method alone. Laboratory analyses, Earth Observation methods, onboard NIR sensing, and agronomic experience each provide different spatial and temporal perspectives on crop development and harvest readiness. While laboratory analyses deliver high analytical precision, Earth Observation methods improve the understanding of field variability and crop maturity dynamics throughout the growing season.

The results further showed that similar average harvest values may still conceal important biological and spatial differences affecting silage quality, crop stability, and final utilization efficiency. Rather than replacing conventional agronomic approaches, the proposed framework highlights the value of combining complementary monitoring methods to support practical harvest decision-making under real farming conditions.

The future of practical silage management will likely depend not on replacing agronomic experience, but on improving the interpretation of increasingly complex spatial and temporal data under real farming conditions.

Conclusion of the Hybrid Observation

The hybrid comparison demonstrated that under heterogeneous foothill conditions affected by severe drought stress, the selection of suitable maize hybrids may significantly influence the final stability and homogeneity of the crop stand. Earth Observation monitoring revealed that some hybrids maintained a more balanced canopy development and maturity progression even under uneven water availability. The results suggest that selecting hybrids with stable performance under variable moisture conditions may help preserve harvest quality and improve crop uniformity during dry seasons.

Conclusion of the Hydrogel Observation

Although onboard NIR sensing did not detect statistically significant differences between the monitored variants, laboratory analyses and harvested biomass evaluation indicated a positive influence of hydrogel application on cob development and final yield. Earth Observation monitoring further revealed a higher proportion of the hydrogel-treated area within the optimal harvest interval, suggesting improved synchronization of crop maturity. The results indicate that hydrogel application may contribute to more uniform harvest conditions, improved cob maturation, and potentially higher starch accumulation under variable environmental conditions.

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