

## **New technologies to monitor and improve silage quality from field to feed-out**

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**Keywords:** Fresh forage, Silage, Portable Near Infra-Red Spectroscopy, Spectral Imaging, novel technologies

### **Introduction**

More than ever, the agriculture and food production industries are facing the challenge of establishing a permanent link between consumer and environmental protection, animal welfare, quality control and economic sustainability. These complex requirements need a suitable systematic approach such as the concept of "Precision Livestock Farming" (Schulze et al., 2007). An integral part to this is precision silage production and utilisation, and many questions require answers before proceeding on the role of new tools and technologies in improving silage management, quality and feeding. Precision crop husbandry has become a very important tool for use on arable farms. Advances have been made with the use of farm vehicles with global position systems (GPS) through to unmanned aerial vehicles (UAV) fitted with various imaging technologies. All advances have the sole purpose of improving the precision with which many operations are performed on-farm, with the overall aim of increasing production whilst reducing inputs. Such approaches have the potential to improve profitability and reduce the environmental impact.

Livestock agriculture has, to some extent, been slow to utilise technological advances in many aspects of their operations. The production, ensiling and feeding of forage crops is central to most dairy production systems and is important in many beef production systems. Without high quality ensiled forages these ruminant production systems cannot maximise the use of home grown forages in their total mixed rations.

This paper aims to investigate monitoring technologies that could have the potential to enhance the quality of ensiled forages for feeding to ruminants and the pros and cons of each approach will be assessed. The paper will be split into 3 subsections, namely growing, harvesting and ensiling, and feeding. The goal of this review is to highlight technologies that are available now or through further development could be available in the future to give forage managers practical 'Silage Decision Support Tools (SDST)' to aid in the efficient production of ensiled forages that meet the quality (both nutritive and hygiene) requirements of the livestock they will be fed to. To close the circle, new perspectives of silo design for automated feeding systems will be discussed. Throughout this review we will examine other industries with related challenges and assess their technologies for application to ensilage. In some situations there is no current SDST available so we will highlight the need and 'throw down the gauntlet' to developers to provide solutions. However at all times we must bear in mind the quote from Stephen Hawking 'the greatest enemy of knowledge is not ignorance; it is the illusion of knowledge'. In other words we must only promote these technologies if they are providing accurate information on which informed management decisions can be based.

### **1. The role of technology in growing silage crops**

The key to successful growth of quality forage for ensiling is a chain of decisions that starts with sowing in the optimal conditions, applying fertiliser and agro-chemicals appropriately with minimal

wastage, promoting good chemical composition of the plant for ensiling and feeding, and achieving a high biomass yield. In addition, long-term sustainability goals should be considered, such as building soil fertility and maintaining local biodiversity. In these regards, there are many technologies available, such as those utilised in precision arable production, which could be applied within the livestock industry to create a 'precision forage' approach to silage-making (Schellberg et al. 2008). We begin this review, by considering technologies that show promise for forage monitoring and how those may be combined with bespoke machinery solutions in the future with the ultimate goal of creating fully-automated forage production systems.

#### ***Current technology for forage assessment***

Walking fields to observe crop health, presence of weeds, and plant maturity has historically been a necessary but time-consuming duty for the livestock farmer. Some tools already exist to aid the farmer in making predictions of biomass yield during this process. The earliest examples being rising plate meters that measure compressed sward height (Earle and McGowan 1979) and electronic capacitance probes (Michell and Large 1983); however, it has been shown that predicting yield using these devices has a high margin of error (Kallenbach, 2015), and is labour intensive. More recently, ultrasonic devices for biomass yield measurement have been developed (Fricke and Wachendorf 2013), some of which are designed to be mounted on All Terrain Vehicles (ATVs) for more rapid pasture assessment over large areas although the accuracy of a moving sensor is lower than that of a static unit (Safari et al. 2016). Perhaps the most promising technology that is only just beginning to be utilised in practice for forages, but is already well accepted in arable practice, is to use the reflectance of electromagnetic wavelengths to form images or spectra. When combined with global positioning systems (GPS) these can be analysed to create spatial mapping of crop traits (Wachendorf et al. 2018). The earliest examples of crop phenotyping using image analysis, relied upon the ratio of reflectance of two wavelengths to compute vegetation indices (VIs), the most common example being Normalised Difference Vegetation Index (NDVI) which was shown to be a predictor of crop biomass (Hill et al. 1999). Development of higher resolution equipment over time has allowed for analysis of a broader range of wavelengths, and predictions for many crop phenology traits have been developed based on a range of VIs (Perez-Sanz et al. 2017).

#### ***Future technology for forage assessment***

**Remote vegetation sensing.** Remote sensing using satellite offers a solution to traditional labour-intensive, *in-situ* data collection methods (Ali et al. 2016), and furthermore, data can be delivered directly to the farm office on demand without the need for capital purchase of sensors. Satellite images also enable monitoring of large geographical areas simultaneously so that national and global trends in land use can be mapped (Crowther et al. 2015); however this review will focus on application at the individual farm-scale. The launch of Sentinel-2 satellites in 2015 offered upgraded multi-spectral resolution, increased frequency of coverage, and the ability to record data from red-edge wavelengths (Lemmens 2015) in comparison to older LandSat, Satellite Pour l'Observation de la Terre (SPOT), and Moderate-resolution Imaging Spectroradiometer (MODIS) images, although cloud contamination remains a challenge. The study of Punalekar et al. (2018) has been one of the first to successfully utilise Sentinel-2A data for yield mapping of productive agricultural grasslands in the UK and showed that this approach could also be applied to multi-species leys (incorporating herbs and legumes) with good accuracy. However, there is a need for sensing technologies to deliver greater functionality than yield mapping alone as the feed quality of silage is primarily determined by its chemical composition. Important traits to measure over time in a growing silage crop include protein, fibre, and energy content that are strongly related to plant growth stage and leaf:stem ratio (Fick and Mueller 1989). A further consideration for silage making is the water soluble carbohydrate concentration of the plant as this is an important determinant of fermentation potential (Duniere et al. 2013). The prediction of chemical composition of plant material using high-resolution hyperspectral sensors *in-situ* or under controlled laboratory conditions has been shown to be possible with good accuracy, e.g. in maize and soybean plants (Pandey et al. 2017) and in permanent pasture (Punalekar et al. 2016). However, it has not yet been proven whether the same would be possible using the lower resolution multi-spectral images that are currently available via satellite. At present, the commercial use of close range

hyperspectral sensors is limited by the complexity, cost and sensitivity of the equipment (Mishra et al. 2017).

***In-situ vegetation sensing.*** Whereas satellite data are limited by wavelength resolution, cloud cover, and equipment capability, ground-based sensing solutions can offer increased precision and broader functionality. One example is the recognition of weeds within a crop using algorithms that can detect differing leaf shape of desired and undesired species based on images from low-cost Red, Green, Blue (RGB) cameras (Berge et al. 2012). The specificity of such algorithms has historically limited its application to arable crops; however, advanced machine-learning approaches have proven that weed recognition within grassland is also possible (Sadgrove et al. 2017). Prototype robots fitted with this capability have previously been manufactured (van Evert et al. 2011) although weed recognition capability has been limited to a small number of common species. Another potential function of *in-situ* sensing is to recognise and provide warning of crop disease (Bock et al. 2010). Software that can diagnose plant diseases and disease severity based on an image taken using a smartphone (Hallau et al. 2018) or tablet (Pethybridge and Nelson 2018) are now available but are not yet optimised for forage crops.

Thermal imaging also has the potential to provide additional crop monitoring data. The temperature of vegetation is closely correlated to heat stress. Demonstrating this, Shimoda and Oikawa (2006) used thermal imaging to distinguish between C<sub>3</sub> and C<sub>4</sub> grassland species and monitor their differential responses to hydrological conditions. Responding to heat stress is likely to become increasingly important in temperate climates as global temperatures rise and the frequency of extreme weather conditions increase.

A natural progression in the use of imaging is to move from 2D to 3D images of crop structure. Complex 3D data pertaining to sward structure can be gathered using laser scanning or structure-from-motion photogrammetry (the coupling of two dimensional image sequences with motion). Using such equipment to predict grassland biomass yield has already proven to have a greater accuracy than that of a conventional rising plate meter (Cooper et al. 2017), and potential applications go beyond yield mapping alone. Analysis of 3D plant images can enable automated detection of plant physiology, an example being the quantification of ear number and size in cereal crops (Paulus et al., 2013). Experimentally, the combination of multiple sensors, including 3D laser imaging, into one observation device can result in a wealth of plant physiological data of this kind (Virlet et al. 2017). Applying such technologies to grassland might enable prediction of plant digestibility based on numbers of plants heading and leaf structure, or quantify the value of crops to pollinators through identification of flowers in swards containing legumes. These would be important in the prediction of harvest-readiness to optimise feed value. At present, there is a lack of research adapting and validating these functions for forage crops, especially for forage crops such as maize, legume, and mixed crops (e.g. herbal leys) whose agronomic requirements are more complex than those of monoculture grassland. These technologies also have significant applications in plant breeding to allow rapid assessment of large test populations for more rapid development of new plant varieties (Tardieu et al. 2017). This is particularly needed for the forage crop industry where there are fewer varieties to choose from than for arable crops, and genetic improvement in yield and nutritional variables over time has been slow when compared with the improvement seen in wheat yield over a comparable time period (McDonagh et al. 2016).

***In-situ soil sensing.*** Promoting soil health and structure and ensuring minimisation of nutrient loss due to leaching is crucial to the long-term sustainability of forage systems. At present, measurement techniques are crude, often based simply on observation of soil structure through digging a pit or laboratory analysis of soil samples. There is a need for real-time data to enable the farmer to respond rapidly to changing soil conditions in the short term, as well as monitoring longer-term trends in soil fertility, in order to optimise efficiency. Electrochemical sensors have been developed that are able to measure a number of important soil variables (Warudkar and Dorle 2016). The study of Shaw et al. (2016) is one of the first to consider the development of a nitrogen sensor network designed to be buried in grassland to provide real-time prediction of plant-available nitrogen and leaching risk. Further improvement of such sensors in combination with robotic fertiliser dispensers or irrigation equipment would allow for a much greater level of input efficiency into forage production (Amrutha et al. 2016).

### **Adoption of in-field technology**

Whilst a number of technologies exist that are either already available for forage crops or likely to be available in the near future, a key challenge is to ensure technologies can be integrated into forage systems in an intuitive way. For *in-situ* field sensing the attachment of sensors to existing machinery is a logical first step. For example, mounting biomass, crop weed recognition, or crop disease diagnostic sensors to the arms of agro-chemical sprayers is one way in which precision inputs can be achieved in forage crops (Serrano et al. 2016). Tractor mounted spectral imaging which assesses crop nitrogen content and through immediate feed-back control to variable rate fertiliser spreaders in a 'one-pass' operation are now in practical use (<http://www.yara.co.uk/crop-nutrition/Tools-and-Services/n-sensor>). The system alters nitrogen application rates according to spectral image assessment of the grass crop to maximise yield and protein quality by applying nitrogenous fertiliser to requirement. The system claims reduced lodging at harvest which is obviously a further benefit. Ultimately, the development of robotic machines has the potential to optimise field operations by cutting down on the requirement for labour and fuel and also reduces the risk of soil compaction, although potentially incurring higher capital equipment cost (Shafiekhani et al. 2017). Attaching sensors to UAVs shows promise as a mechanism of collecting close-range, high resolution imaging data without the farmer being physically present in the field (Holman et al. 2016). Combining the output from multiple sensing techniques will allow for the greatest modelling of crop performance and provide the highest level of decision-support. A challenge exists in delivering data to the farmer in a way which is useful and not overwhelming (Adrian et al. 2005); in this regard cross-disciplinary work with software engineers may be required in the future.

## **2. Harvesting and Ensiling**

**Timing of cutting** The technologies discussed in section 1 on growing the crop will enable better assessment to be made by the forage manager on when the optimal point of harvest is reached in relation to the question, 'is the quality correct and is there sufficient yield?' Additional information about crop quality in terms of crude protein, digestibility/energy/fibre content and starch will be at the fore. Mobile NIRS instrumentation (Aunir [<https://www.abvista.com/Products/GB/NIR-4-Farm.aspx>]; Dynamica Generale, [<https://www.dinamicagenerale.com/en-ww/agrinir.aspx>]; Scio [<https://www.consumerphysics.com/business/>]) with wet pre-ensiled crop calibrations have the potential to immediately assess these quality parameters, but they have two important potential drawbacks. Firstly accuracy of sampling of large field areas and sample preparation especially for seed bearing whole-crop forages such as maize and cereals is required to give a precise answer. Secondly, the accuracies of the NIRS predictions need to be validated and regularly updated for a wide variety of geographic, climatic and species/cultivar conditions. Thus technologies based on those discussed earlier will ultimately give a better whole field assessment of both yield and quality. These technologies need to capture the yield and quality data to enable simple calculation of energy and/or crude protein yield/hectare measurements and thus help break the farmers' perception that DM yield is the most important criterion.

Simpler systems based on well-established morphological/phenotypical characteristics linked to mobile phone photography and associated applications (Apps) to predict likely digestibility and energy content are likely in the short term to be more accurate and more widely available to forage managers and should be relatively easy to link to yield estimations as well.

With these technologies to aid the decision making process the only unknown is the effect the weather could have, especially with forage crops such as grasses and legumes on the wilting time and thus the DM content at harvest. With the ever increasing reliance on mobile Apps, the development of one that takes existing and developing technologies that provide yield data, alongside the physiological crop maturity and the DM content of the standing crop in combination with meteorological forecasts of rainfall, wind speeds, temperature and sunlight to predict rates of wilting would be beneficial. Furthermore density and depth of the mown crop could add further information to improve predicted optimum wilt time. Scientific input will be required to provide the wilting data but such an App would provide the forage manager with not only a risk factor for mowing at a specific time on getting to the

ideal forage DM level for ensiling before rainfall but also the wilting time required to hit the target DM content for ensiling, thus enabling more controlled management of the harvesting process and greater control of the DM variability of the ensiled forage. Such an App would not only improve management but would also help reduce DM variability across a given feed-out face of a single silo and thus improve the nutritional balance of forage:concentrate in the total mixed ration (TMR), which ultimately affects diet formulation probably more than any other single factor.

**Disease status at harvest.** Rapid methods that assess disease and microbial status in the growing crop could also assist in forage management. Two technologies of potential use are the measurement of chlorophyll remotely using hyperspectral imaging as a measure of healthiness alongside the development of rapid fluorescence scanning techniques currently used in human health assessments of diseases caused by various fungal infection (Graham 1983) or in the rapid assessment of meat contamination during processing (Ait-Kaddour et al. 2011). Such rapid pre-ensiling methodologies will enable more precise management decisions to be made about the ensiling technology to be used. It may be more appropriate to ensile a more infected region of a field into bales to provide the opportunity to feed this portion of silage to less health vulnerable livestock. In addition pre-ensiled forages with high yeast populations are more likely to require additives designed to control aerobic spoilage.

**Mowing, tedding and raking.** One of the most common problems in silage production is one of soil and therefore *Clostridia* contamination. Initially employing too low a cutting height results in soil contamination, but consequentially all subsequent field based forage manipulations such as tedding, raking and even pick-up with the forage harvester cause further soil contamination. The road construction industry routinely uses GPS assisted technologies. Integral to earth moving machinery are automatic levelling controls whereby the machinery buckets/shovels automatically adjust to a predefined height above the existing surface to ensure the construction is conducted in a human-proofed manner (eg Mouazen et al. 2004; Trimble [<http://www.trimble.com/Industries/Construction/index.aspx>]). With some adjustments development of in-built systems to control mower and rake height above soil level constantly as it traverses the field should be easily achievable. Additional benefits of implementing such feedback control mechanisms during field operations will enable improved total forage yield/hectare/annum to be achieved as the regrowth of the crop will be quicker. Also the more consistent, and in some cases higher stubble height, will improve silage quality by leaving in the field and not harvesting the dead and stemmier, low digestible material which in addition contains the higher population density of undesirable silage microorganisms.

**Monitoring of the mown crop before ensiling.** The most important factor to be able to monitor instantaneously is the DM content and in particular how this is changing with wilting time, alongside this the change in water soluble carbohydrate content relative to the DM would be a useful indicator of efficiency of wilting. Currently sampling and analysis by mobile NIRS with the appropriate calibration is the most imminent approach. Whilst this does require a good field sampling regime, the results are instantaneous once analysis has been conducted. The issue with remote sensing by spectral imaging of the entire field is that this image is likely to only see the top of the laying sward which can have a considerably higher DM content than the forage hidden beneath.

**Forage harvesting** Modern forage harvesters, particularly those from Claas and John Deere have embraced technologies in an attempt to provide farmers with more information. Sensors based on conductivity can measure DM content and temperature of the forage as it passes through the spout. Temperature assessments of forage as it leaves the spout of the forage harvester, we believe are of increasing importance in enabling the forage manager to better manage harvesting in a climate changing world. In an increasing number of countries, forage harvesting is occurring at temperatures in excess of 40°C. The efficacy of standard inoculant silage additives becomes highly questionable at these temperatures (Marley 2017), yet the likelihood of a malodorous silage fermentation increases (Adesogan 2009) due to the temperature being nearer the optimum of the undesirable epiphytic Enterobacterial and Clostridial populations than the lactic acid bacteria. Once forewarned of the higher temperature risk factor the forage manager can make an informed decision to switch from an inoculant to a chemical preservative.

More advanced methodologies involve the use of spout mounted NIRS instrumentation that are calibrated for DM, crude protein and starch content. This instrumentation does need to be properly calibrated which is an underlying question with regard to the accuracy of the results. The latest forage harvesters have feedback control based on DM content, reducing the theoretical length of chop as DM content increases. In addition to this as the forage passes from the pick-up reel into the chopping chamber the yield can be predicted by the force exerted during the process. The manufacturers even suggest that this prediction is more accurate if on 2-3 occasions per field the trailers are weighed and the collected data are input into the prediction model on the forage harvester. However the development of weigh cells that can be directly fitted to specially adapted trailers removes the need for any predictions, as data can be collected directly and accurately from each and every load harvested. These data are invaluable to precisely measure yield and if linked to GPS for each load can combine with yield, fertiliser application and protein content maps used in part 1 crop growing, to improve the accuracy of the prediction models used in those technologies.

In addition the use of the trailers fitted with weigh cells has two further advantages. A patent (Strzelecki 2016) enables remote communication between trailer weigh cells and the forage harvester silage additive applicator allowing instantaneous adjustment of the flow rate of application of an additive to ensure correct application. An additional advantage of this system is that the operator of the forage harvester can observe the trailer weight in real-time and can visualise when forage is leaving rather than entering the trailer, and thus operators using this approach have stopped over filling trailers and thus reduced field losses of forage.

**Clamp filling.** Packing density and moisture content of silage are of great significance in improving silage quality. A lower packing density means a higher porosity, which could result in more oxygen remaining in the silage and leads ultimately to lower silage quality with higher storage losses and greater propensity to problems of aerobic spoilage. The traditional method for determining the packing density of silage is to calculate its gross density from mass divided by volume. The disadvantage of this method is that it is unable to show density differences at specific sites, unless measured in different regions of the clamp by the coring based methodology (Ruppel et al. 1995). The  $\gamma$ -ray scanner is an effective tool to analyze the packing density in two dimensions with a relative error of measurement around 1% (Fuerll et al. 2008; Mumme et al. 2008). However, the  $\gamma$ -ray scanner is not widely applied due to its high cost and the potential danger to health (Sun et al. 2010). In recent years, the penetrometer technique has been used to measure the packing density of silage because it is straightforward to calibrate and can provide reliable data (Perumpral, 1987). Meng et al. (2018) proposed a compound sensor design based on American Society of Agricultural and Biological Engineers (ASABE) standards as a novel technique for evaluating the moisture content and density of silage. In this compound sensor, the moisture electrode and strain gauges were embedded in an ASABE standard small cone, which made the compound sensor capable of measuring the packing density and moisture content of silage simultaneously. The results appear promising as the packing density and moisture content of the silage are linearly related to the outputs of the compound sensor and both coefficients of determination were greater than 0.93. Mobile NIRs has also been investigated as a technique to measure silage density (Davies et al. 2018). The initial developments look promising; however its assessment has been on open clamp faces and not during clamp filling, and more datasets are required to ensure its validity.

Until direct measurement of density while packing is possible, it may be necessary to develop tractor/operator-based solutions, as with the field operations of mowing, tedding and raking. Filling layer depth could be controlled by similar systems developed from the construction industry. Holmes (2006) paved the way for this approach using web based excel sheets to improve silo filling (<https://fyi.uwex.edu/forage/harvest/> (Floor Length to Achieve Bunker/Pile Silo Filling Layer Thickness Calculator)). Further development of an interactive app that utilises input data of trailer forage weight, trailer volume and forage DM content alongside loading shovel width and volume dimensions would be able to compute the distance each loading shovel/trailer should be spread over the clamp surface to maintain the optimum layer depth and by linking to the tractor GPS could ensure it is accurately achieved.

### 3. Feeding out

The efficiency and the silage quality of the feeding phase are greatly influenced by the previous phases from the field to silo opening. Since high quality conserved forages are crucial to maximizing efficiency and sustainability of livestock farms, the objective is to feed animals a uniform high quality silage over the whole profile of the silo for the entire year (Wilkinson and Davies 2013; Borreani et al. 2018). Utilisation of the technologies discussed in parts 1 and 2 will hopefully have enabled a silage clamp with uniform ideal quality to have been produced. As previously stated, silage quality is composed of four pillars: nutritive (macro and micro), fermentative, microbial and contaminants. Properly informed management practices and decisions from the harvesting stage, through wilting and ensiling phase to feed-out phase are the only means to achieve consistently high quality silage during progression both across a clamp and from front to back.

Possibly the most important factor affecting silage diets are the contents of dry matter, crude protein and utilisable energy, and variability within a single feed-out face of the silo can be large. Thus rapid methods to accurately assess this for every feed mixer load are vital as these have a major effect on the accuracy of diet formulation and DM intake. Reference laboratory methods for DM assessment are time-consuming and cannot be applied to the daily changes in diet composition; therefore better moisture sensing techniques for modern agricultural with on-line moisture monitoring are needed (Nelson and Trabelsi 2004). Currently, new promising real-time technologies, based on microwave free-space measurements involving attenuation and phase-shift determination and density independent functions, are available to permit reliable moisture sensing applicable to moving grain in which bulk density variation occurs (Nelson and Trabelsi, 2004). These advantages, along with promise for a universal moisture calibration, should encourage the development of microwave measurement systems to be applied to silages (Perricone et al. 2017).

One of the most important factors influencing silage quality and animal performance during feed-out phase is the control of aerobic deterioration, probably the most significant problem for farm profitability and feed quality worldwide. It is now recognized that the changes during the feed-out phase are equally as important as those in the closed silo from the viewpoint of preserving nutrients and maintaining good hygienic quality of the silage (Wilkinson and Davies 2013). Several factors affect silage quality and nutritional losses during feed-out, many of which should be controlled in the field during crop growing and during harvesting and ensiling. Key factors affecting silage quality at feed-out are the daily feed-out rate, the fermentation profile and the incorporation of top and side (waste) deteriorated silage. By planning the silo size to achieve the correct daily feed-out rate, which depends on the season and latitude, and by properly sealing and covering the silo to minimize oxygen penetration during the conservation phase, many of these issues can be solved. Feeding either aerobically or anaerobically spoiled silage can have numerous impacts on the animal from increased risks of contaminants in the feed to reduced intake and production (Borreani et al. 2018).

During feed out, different stages of aerobic deterioration can be present at the same time at the silo face. Mouldy silage can be easily appraised visually; unfortunately, there may be other parts of the silage face that are rapidly spoiling but appear no different than stable silage. The ideal would be to detect all spoiled and spoiling silage and avoid its inclusion in the feed ration. The accurate evaluation of the microbiological and chemical quality of the whole working face is currently impossible in an accurate, timely and cost efficient way to be performed routinely on the farm during the feed-out phase. Hence, simple methods of enabling the forage manager to quickly and accurately assess silage quality and the extent of aerobic deterioration at the silo face are essential.

The first step in determining what analytical approach to use in silage evaluation is to define the objectives of testing. Silage testing can be summarized by the three objectives: a) Providing nutritional inputs and DM content to formulate ruminant diets; b) Evaluating potential hazards to safety and quality of milk and dairy products (mycotoxins, *Listeria*, yeasts and moulds and spore-formers); c) Evaluating conservation efficiency (DM losses and spoiled silage to be discarded). If these can be done quickly and precisely, then selective feeding actions can be employed to improve farm silage efficiency.

Unfortunately, with on-farm silages, most microbial deterioration is invisible initially and may only be detected by a temperature rise in the forage (Borreani and Tabacco 2010). Since the oxidation process is accompanied by the evolution of heat, an increase in temperature is a convenient indicator of the extent and intensity of aerobic deterioration and can have application in alerting farmers to the onset of aerobic deterioration. To monitor aerobic deterioration during silage production, the internal temperature of silage is often used as an indicator or alarm (Borreani and Tabacco 2010). Several systems to measure temperature of the working face of a silo can describe the areas involved in aerobic microbial activity that are otherwise invisible. One method consists of burying temperature loggers inside the silo at the time of silo filling and retrieving them at feed out. Green et al. (2009) proposed burying wireless sensor nodes to precisely monitor and measure the temperature inside a silage stack. These sensors reliably transmit the data to a network model to predict the normal temperature variations of the silage using the air and soil temperature as inputs, and could detect the abnormal temperature variations inside the silage caused by silage deterioration.

A first attempt to establish which area of the silo was subjected to aerobic deterioration at the farm level by means of a probe thermometer was made by Ruppel et al. (1995). Alternatively infrared thermography is a non-invasive technique capable of detecting thermal radiation from the surface of any object; heat-sensing digital cameras can capture in a single picture all temperatures of the working face, and may reduce costs associated with personnel and chemical reagents used for conventional assessment of silage aerobic stability (Addah et al. 2012). However, temperature measurement by infrared thermography is highly influenced by weather (sunny, cloudy, rainy, etc.), the time of the day, the exposure of the silo face to direct sunlight, wind, and the homogeneity of the feed-out face. To overcome these issues, Clemente et al. (2015) proposed that reliable data could be obtained by removing about 0.1 m from the silo face before shooting the image.

Monitoring silage O<sub>2</sub> concentration and temperature can provide a critical insight regarding silage quality. Bochtis et al. (2011) suggested the need for the development and implementation of dedicated decision systems for the prediction of quality parameters in ensiled biomasses, for example, by predicting the occurrence of oxygen entering the silage, by monitoring the temperature and the outside weather conditions, and incorporating such measures into designated decision support systems and by extension into farm management information systems. They showed that the system can provide the forage manager with information about biomass quality parameters by graphical visualization as a first step and, as a second step, the system issues alerts depicting real deviations between actual and predicted values of the monitored properties. Sun et al. (2015) proposed the use of the Clarke oxygen electrode as an *in situ* biosensor for simultaneous monitoring of O<sub>2</sub> and temperature to monitor maize silage aerobic deterioration.

Oxygen in silage is central to the deterioration of silage quality and thus measurement of it could provide useful decision-making information. Even though the gas chromatography measurement is very accurate, the available methods are time consuming and unable to monitor silage O<sub>2</sub> dynamics. Shan et al. (2016) focused on assessing three types of commercial O<sub>2</sub> sensors, including Clark oxygen electrodes (COE), galvanic oxygen cell (GOC) sensors and the Dräger chip measurement system (DCMS). They concluded that in terms of measurement quality, the calibrated COE and the GOC sensors reported similarly high accuracies in maize silage. The reduced accuracy of the DCMS, especially at low O<sub>2</sub> concentration, was probably caused by the relatively high levels of CO<sub>2</sub> in the silage. They concluded that the GOC provided the least costly option but was unable to simultaneously measure O<sub>2</sub> and temperature, whereas the COE had a high performance to cost ratio (Shan et al. 2016).

Some companies propose the use of a portable electronic nose to quickly identify traces of organic, biological and chemical compounds with accuracy in corn and wheat silages (<http://www.estcal.com/blog/quality-assessment-corn-silage>). The idea is to identify mouldy silage by quantifying the musty odour. Preliminary analyses were performed on corn grain to verify the capability of portable electronic nose to identify sour, musty and good corn samples. The chromatogram results of testing all types of corn samples displayed the capability of quantification and difference among the samples: the lactic acid peak in the sour samples was clearly visible; the



distinctive compound peaks of musty corn were different from other samples and were not present to any large extent in other samples; the relatively odour free chromatograms of good corn samples were distinct as well. These systems have been tested for silage (Masoero et al., 2007) and the use of volatile odours are used widely in the cheese and wine industries as methods to assess fermentation products of microbial origin (Liu et al., 2004; Bartowsky, 2012). Thus the potential of these approaches warrants significant further investigation for detecting not only markers of aerobic spoilage but also pathogenic bacterial contamination of silage. The use of hand-held instruments such as portable NIRS increases the potential for farmers to take more samples because analysis is quick and relatively cheap (Modroño et al. 2017). The NIRS analysis allows the characterisation of concentrate and forage feed sample components of the total mixed ration accurately and precisely (providing the prediction model is appropriate). Construction of new dairy cow farms and modernization has begun over the last few years. Modernization of dairy production has resulted in rapid growth of herds being handled on farms and the need to reduce labour have brought the development of integrated automatic solutions, such as administration of concentrates, automatic milking systems, cleaning of manure, loose handling of cows, and management of the microclimate (Saliņš et al. 2012; Bisaglia and Brambilla 2017). With this in mind some companies have produced fully automated feeding and feed mixing robots (Saliņš et al. 2012). These automated systems move forages and feeds into the feed kitchen, in which the silages and other feeds are stored. Saliņš et al. (2012) assessed, on several commercial farms, forage distribution robots in comparison with tractor mixers-distributors. They concluded that the feeding robot can compete with mobile distributors even if concentrates are included in the total mixed ration and even when they are not stored in specific feed stations. Robotic systems have opened up new perspectives and requirements with regard to technologies to monitor and improve silage quality and aerobic stability for implementation and successful application at farm level, only time will tell whether these improve or reduce the risks of aerobic stability at feed-out. However by removing the human element it is our belief that they will reduce both aerobic spoilage and variability in forage feed-out management.

The current trend is to identify integrated automatic solutions, which interact with each other and can represent the start of what will be the true development of automation in the future. The modern farm of the future with up-to-date technological solutions are already being implemented with: loose handling of cows, milking in halls with high-productivity milking equipment or automatic milking systems (AMS), TMR or use of precise feeding technology and automatic manure removal. Introduction of all these different technological solutions is possible and will become the norm on progressive large dairy farms; thus it is essential that silage quality, both nutritive and hygienic quality, is maximised for the livestock it is being fed to.

### Summary

The success of the automated livestock farm using new technologies will be enhanced if similar robust technological approaches for silage production can be developed and implemented but it is essential that these technologies provide accurate and useful information to enable the forage manager to adapt the system from field to feed-out to account for the unforeseen variables such as weather and climate that can vary year to year. Thus the monitoring and feedback technologies reviewed here need to be robust, cost effective and provide rapid information in an easily digestible form for the forage manager to make decisions on factors from: field crop nutrition and growth yields, optimal harvesting time through to harvesting and ensiling quality, finishing with feed-out quality and monitoring of aerobic deterioration. If successful, this will help ensure that the highest quality silage is being consumed and utilised within the most precisely formulated TMR by the livestock on each farm utilising such approaches.

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