Successes and challenges of near-infrared spectroscopy in the avocado value Chain

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ABSTRACT

Two near-infrared spectrometers (NIR) were tested at various points in the avocado value chain. The first was a handheld unit for estimating dry matter content. When measurements were taken with the fruit skin removed, the R2 = 83% and SEP = 2.25% DM for 'Fuerte', 'Hass', and 'Mendez #1' ('Carmen®-Hass') combined. A comparison between the conventional method to determine dry matter and this NIR method, showed that, on an orchard basis, 76% of the DM-values being within 1.5% DM of each other. After a robust model has been developed, handheld NIR can be used to quickly determine dry matter of avocados pre- and postharvest.

The second unit was a packline-mounted T1 unit from Taste Technologies for application in a packhouse or ripening facility. On hard fruit, the unit was able to eliminate class 1 fruit with orchard cold (frost) damage with accuracy of up to 90%, depending on severity of the damage. This unit was used on a semi-commercial basis at Westfalia Packhouse in 2014. Furthermore, it was able to estimate dry matter with a standard error of prediction (SEP) of 1.9% DM and R2 = 76% - comparable to the handheld unit.

For ripe fruit, the T1 was able to detect diffuse flesh discolouration (grey pulp) with an accuracy of about 80%, depending on severity. Other disorders and diseases were not consistently detected due to the isolated nature of these defects in the fruit flesh. The economic feasibility of online NIR is complex and needs to be determined case by case.

Keywords: Maturity, Dry matter, Non-destructive testing, Fruit quality, Frost damage, Grey pulp.

INTRODUCTION

Non-destructive testing of avocado maturity and fruit quality using near-infrared spectroscopy (NIR) has been investigated by various researchers (Schmilovitch *et al.,* 2001; Clark *et al.,* 2003; Blakey *et al.,* 2007; Blakey *et al.,* 2009; Blakey & van Rooyen, 2011; Blakey, 2012; Blakey, 2014). The online non-destructive determination of fruit maturity and quality is desired by packhouses and ripening centres (RCs) as a means to identify and reject immature and poor quality fruit from the supply chain at these two critical handling points, i.e. before packaging and shipping, and distribution to supermarkets, respectively. Another option is to use a portable (i.e. handheld) instrument to determine fruit maturity and quality at locations away from the packline. This can be throughout the supply chain.

Fruit Maturity

Early season avocado fruit fetch a price premium because demand exceeds supply. Growers are therefore eager to supply this market. In South Africa, this has resulted in some growers harvesting and supplying immature fruit. Immature fruit does not complete ripening and the quality of the fruit is poor. This resulted in the South African Avocado Growers' Association (SAAGA) implementing a campaign against the supply of immature fruit (Muller, 2010). A portable means to determine fruit maturity would allow for the rapid testing and removal of immature fruit from the supply chain.

Days to Ripen

The variation in days to ripen results in increased costs for a RC, and fruit quality loss as fruit can be bruised after repeated handling. As such, RCs desire to reduce this variation in ripening. The ability to pre-sort fruit before ripening, preferably at the packhouse before export, would be highly advantageous.

Fruit Quality

A major avocado fruit quality disorder is grey pulp – also termed mesocarp discolouration or diffuse flesh discolouration (White *et al.,* 2004). The incidence of the defect increases considerably later in the avocado season, and limits the export season in South Africa. Grey pulp develops as the fruit ripens, but the defect is strongly related to preharvest factors (van Rooyen & Bower, 2005) so it would be commercially valuable to sort fruit prone to grey pulp at the packhouse and/or at the RC.

Avocado fruit are sensitive to orchard cold damage. The fruit flesh turns brown and the damaged tissue does not ripen. The fruit skin can turn red or bronze but there is not a strong correlation between skin and flesh symptoms. Therefore it is not possible to visually sort fruit visually with any degree of accuracy. A non-destructive method to detect frost damage offers a means to recover undamaged fruit.

Objectives

1. Calibrate a handheld NIR spectrometer for avocado moisture content (MC) and determine if, and where, this instrument is commercially viable.
2. Develop calibrations models for an online NIR spectrometer for avocado MC, internal defects, and days to ripen. Then determine if, and where, the instrument is commercially viable.

MATERIALS & METHODS

Handheld NIR

A Phazir 1018 handheld near-infrared spectrometer (Thermo Scientific, Wilmington, MA, USA) was used in this study. For the calibration of the instrument, fruit were scanned at four to six points around the circumference. Moisture content (MC; the complement of dry matter) was measured gravimetrically within a few hours of harvest; 1.0g samples were oven-dried at 70-75°C for at least 24 h (Blakey, 2013; Blakey, 2014). The model was developed between 2011 and 2013 and then validated in 2014 and 2015. About 10,000 samples were used in the final models, due to a limitation in the instrument's software (Polychromix-MG v 3.101.0.0).

Online NIR

A T1 (Taste Technologies, Onehunga, New Zealand) NIR spectrometer was used. MC was measured according to the above protocol. For the calibrations for defects, fruit were scanned on the day of harvest, approximately 12h after removal from 28 d of cold storage (once the fruit temperature had reached room temperature), and at ripeness. Fruit were scanned twice each, with a 180° rotation between scans. Fruit were cut and assessed at ripeness according to White *et al.* (2004). Models were developed between 2010 and 2013 according to Blakey (2012). The model for grey pulp was validated in 2013 using 'Fuerte' that was stored at 5.5°C for 28 days.

RESULTS AND DISCUSSIONS

Handheld NIR

The MC of 'Fuerte' fruit could be estimated with an acceptable level of accuracy, but the accuracy of MC for 'Hass' and 'Carmen®-Hass' was poor if the skin was not removed. A model for MC with the fruit skin removed combining all three cultivars was developed. This is preferable because the operator would not have to change models when scanning different cultivars, and it may be useful for cultivars not included in the model.

The external validation of the handheld NIR showed that the combined model for flesh MC with the skin removed is stable (Figure 1) with an error almost equal to the conventional gravimetric method used at Westfalia Fruit Packhouse (Table 1).

The predictive ability for the model was lower for 'Hass', but this appears to be because the gravimetric MC was unexpectedly too low when compared to the previous week and results from neighbouring orchards. As with conventional methods to determine fruit maturity, some interpretation of the results is necessary to obtain logical results.

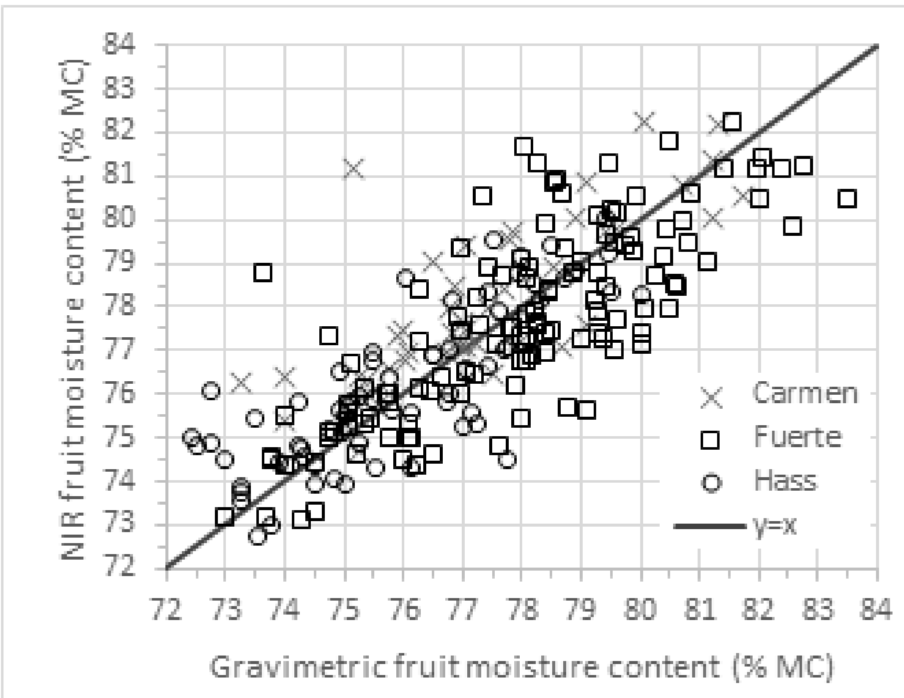

Figure 1: External validation of 'Carmen®-Hass', 'Fuerte', and 'Hass' in 2014 and 2015. Fruit flesh moisture content (MC) determined gravimetrically vs. handheld NIR (skin removed) where each data-point is for a Westfalia Fruit orchard at a specific date.

Table 1: Co-efficient of determination (R2) and standard deviation (SD) for fruit flesh moisture content (MC) determined gravimetrically and by handheld NIR in the external validation. SD was calculated per orchard per date

Cultivar	R2	SD Gravimetric (% MC)	SD NIR (% MC)
Carmen	78%	1.8	1.9
Fuerte	78%	1.9	1.9
Hass	71%	2.1	2.0

Sources of Error

There are a number of sources of error when calibrating and using the handheld NIR. Some of these are discussed briefly below.

1. Error in oven-drying method. This can be checked by including multiple samples from the same fruit so that erroneous values can be detected and removed.
2. Water stress in-field. Fruit from dryland orchards, or from water stressed trees, have shown high variability in the MC results (data not shown).
3. Temperature. The principle of NIR is based on the chemical bonds within molecules. These are affected by temperature, so large temperature variations will increase the error in NIR readings. Also, fruit with a high pulp temperature will likely be dehydrated.
   Cold storage and ripening. The texture and chemical composition of avocado fruit changes greatly during cold storage and ripening (Blakey *et al.,* 2012; Blakey *et al.,* 2014). Fruit MC should be measured as soon after harvest as possible and is a non-meaningful parameter after cold storage or once fruit begin to ripen.
4. Poor contact between instrument and sample. Care should be taken to have good contact to reduce "leak light" increasing noise in the spectra.

Commercial Considerations

The recommendation is to use the average fruit MC (sample size of at least 4 fruit and at least 2 measurements per fruit) rather than consider individual fruit. There is considerable natural variation between avocado fruit so it is advisable to maximise the sample size for better results.

At Westfalia Fruit, pre-season maturity testing includes MC, but also includes samples to determine fruit quality upon ripening. The legal minimum MC and acceptable fruit quality have to be achieved before an orchard can be harvested. However, there is a bottleneck at the MC laboratory, due to the scale of the Westfalia Fruit operation. The handheld NIR can be used to ease this bottleneck by increasing the analysis speed.

Three seasons were required to develop a stable and accurate model for this handheld NIR. This concurs with Wedding *et al.* (2011). The cost of a unit, a long lead-time, and specialised skills required to calibrate the instrument, are prohibitive to most companies wishing to make use of this technology.

Online NIR

Fruit Maturity

The online NIR was able to measure the MC of avocado fruit with fairly good accuracy (Table 2). This is slightly more accurate than the handheld NIR, and also faster (<1s vs. 6s). The improved accuracy is likely due to a greater volume of fruit flesh being included in the scan. However, there is a complication in that there is statistical bias (i.e. shift by a constant value) of the online NIR MC results (Figure 2A), and a correction factor has to be applied to improve the accuracy (Figure 2B). It is relatively easy to determine this constant by measuring the MC of a sample of fruit gravimetrically and via NIR. The accuracy of the model was lost when the MC was less than 72%, but this is not commercially relevant because it is well below the minimum maturity of commercial cultivars.

The use of online NIR to measure MC could only be implemented at the packhouse because the measurement of fruit moisture content is not meaningful after cold storage and ripening.

Table 2: Co-efficient of determination (R2) and standard error of prediction (SEP) for fruit flesh moisture content (MC) determined gravimetrically and by online NIR.

Cultivar	R2 (%)	SEP (% MC)
Carmen	80	1.6
Fuerte	80	1.5
Hass	88	1.6

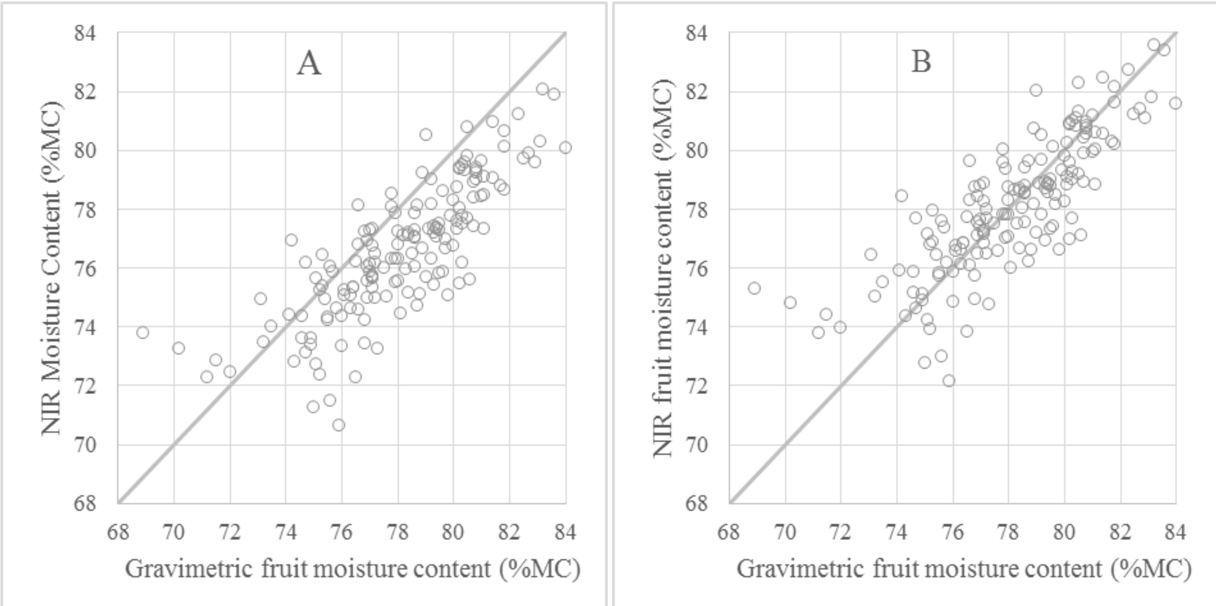

Figure 2: Comparison between gravimetric fruit moisture content vs. NIR fruit moisture content, without a correction factor (A) and with a correction of 1.5% MC (B) for 'Carmen®-Hass' fruit from two orchards from two disparate farms.

Days to Ripen

An accurate, stable model to predict the number of days to ripen at harvest could not be developed. It was hypothesised that there was too much unaccounted for natural variation within the fruit, which was exacerbated by waxing and by cold storage. There was also no correlation between fruit MC and days to ripen.

Fruit Quality

The accuracy of the online NIR for defects depends on the threshold values that are used to sort fruit into different classes. The operator can change the threshold value to eliminate more defective fruit, but with the trade-off of erroneously eliminating more defect-free fruit. By making a quantitative measurement qualitative, there will by some misclassification of the fruit on either side of the threshold value. It is relatively straightforward to develop a model that discriminates between defect-free fruit and fruit with a severe symptoms. The greater skill is in developing a model that can accurately discriminate between fruit with a similar severity of the defect. As an example, the fruit in the validation were sorted into three classes (Passed, Marginal, and Failed) using two threshold values (Figure 3). This was done to improve the separation between fruit without grey pulp ("clean") and those with more severe grey pulp. The fruit that is classified as marginal can then be sorted with the "clean" fruit or the fruit with more severe grey pulp (Table 3 and Table 4) – depending on the desired Quality Assurance (QA) standard. If marginal fruit and severely affected fruit are grouped together, there was a reduction in the incidence of defective fruit in the clean fruit from 27% to 24% but the percentage of passed fruit decreases from 70% to 53%. These levels would adjust accordingly, depending on the threshold values selected and the incidence and severity of the grey pulp.

Fruit with frost damage were sorted from clean fruit with varying degrees of success (Table 5). The accuracy was affected predominantly by the severity of frost damage. The discrimination was markedly better in fruit from orchards that had a high incidence of severe frost damage (e.g. Farm A), than orchards with only slight damage (e.g. Farm B).

Table 3: Summary table for NIR sorting of ripe 'Fuerte' fruit with NIR. Italic text is correctly classified, roman text is incorrectly classified

Decision	Clean	Grey Pulp	Total
Passed + Marginal	51%	19%	70%
Failed	11%	19%	30%
Total	62%	38%	100%

Table 4: Summary table for NIR sorting of ripe 'Fuerte' fruit with NIR. Italic text is correctly classified, roman text is incorrectly classified

Decision	Clean	Grey Pulp	Total
Passed	41%	13%	53%
Marginal + Failed	22%	25%	47%
Total	62%	38%	100%

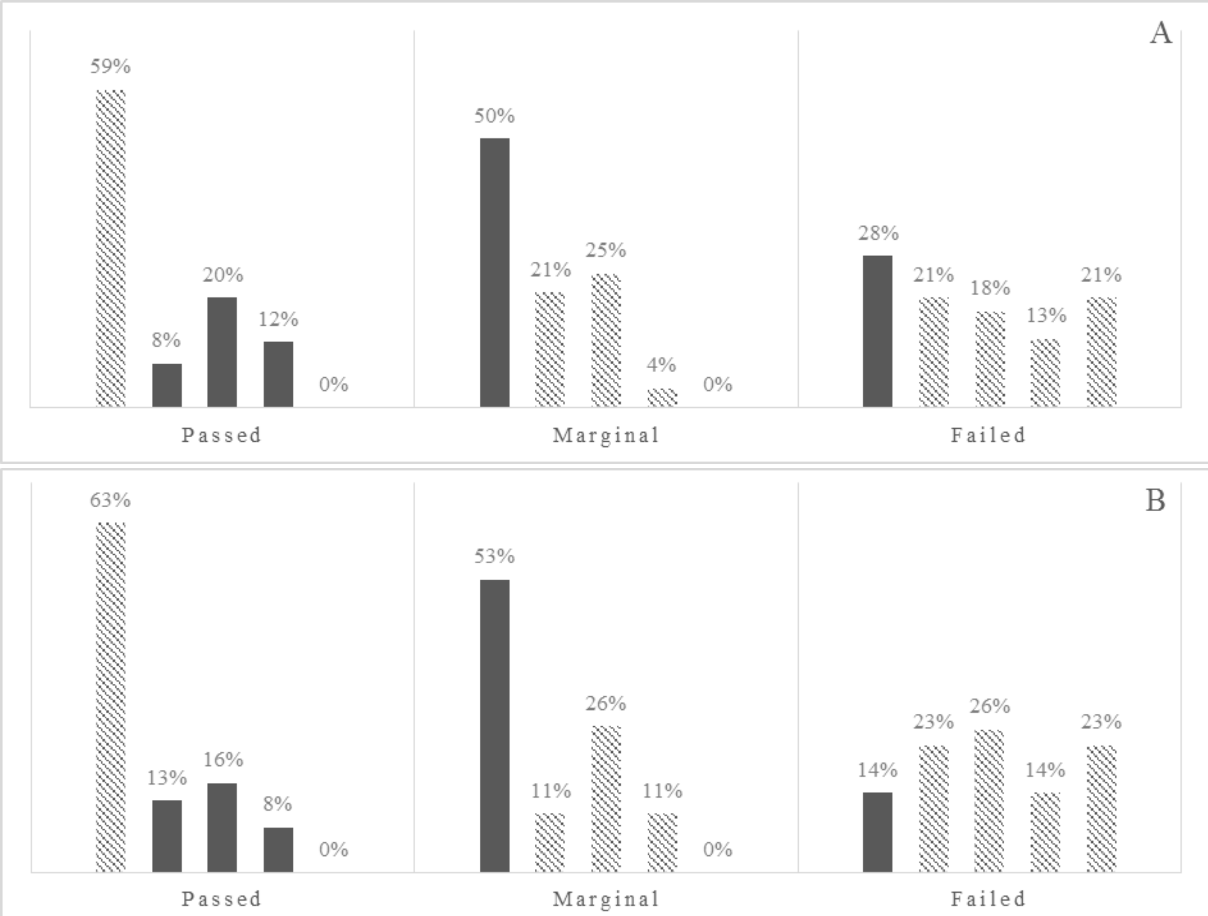

Figure 3: Results from sorting 'Fuerte' fruit after 28 days cold storage at 5.5°C (A) and at ripeness (B) into three categories (Passed, Marginal, and Failed) using online NIR. Shaded columns indicate correct classification and solid columns indicate incorrect classification by the NIR. Columns from left to right are ratings of 0 (no grey pulp), 0.5, 1, 2, and 3 (severe grey pulp). The marginal fruit were rejected. The incidence of grey pulp was 38%.

Table 5: Correctly and misclassified fruit from three 'Hass' orchards from three farms in 2010 and 2011

Farm	Correctly Classified Fruit (%)	Misclassified Fruit (%)	
		Frost	Clean
A	92.6	3.7	3.7
B	69.5	2.0	28.5
C	86.2	13.8	0

Sources of Error

It is desirable to have more distinct sorting between defective and defect-free fruit. There are a number of potential sources of error when using online NIR that can reduce the accuracy of sorting. These are discussed briefly below.

1. Undetected defect due to a limited field of view. Small, isolated defects can be missed by the NIR because the entire fruit volume is not scanned. Examples are stone cells from insect damage, bruising and fungal decay. This can be improved with modifications to the packline to increase the volume of the fruit that is scanned. This is not a problem for extensive and/or diffuse defects like frost damage and grey pulp.
2. Incorrect threshold. The threshold for sorting between defective and clean fruit needs to be continually monitored to optimise the accuracy of sorting.
3. Non-visible defect detected by spectrometer. It is hypothesised that there are fruit that do not exhibit visible defects but are classified as defective because the fruit flesh is physiologically compromised but the symptoms are not yet visible. This would need to be confirmed with a biochemical assay.
4. Natural variation in fruit. Fruit origin is known to affect the biochemistry of avocados (Donetti & Terry, 2014) and is likely is reduce error if not included as a variable in the model development.

Commercial Considerations

Compared to apples and citrus, it is a challenge to develop accurate, robust NIR models for avocados because of the non-spherical shape, a large seed with variable size and a thick skin. Users should accept that the models will not be as accurate as those for these fruit crops.

Non-destructive quality determination (viz. online NIR) does offer a point of difference in the increasingly competitive avocado market but the investment in online NIR is considerable so the technology should add measureable value to production to warrant commercial roll-out. Careful consideration is needed before a company commits to using NIR and this would have to be done on a case by case basis depending on the NIR supplier and local conditions. Online NIR can either be installed at the packhouse in the country of origin, or at the RC in the destination market. These options are discussed below.

Packhouse

Installing the NIR at the packhouse would eliminate the poor quality fruit earlier in the supply chain, before postharvest costs are incurred. The installation at the packhouse could be on a "pre-sort packline" with one or two lanes, or on the main packline. The packhouse would have to analyse the economics and engineering aspects of both situations. The minimum number of NIR units required, the cost of the packline/s, and the processing/standing time of the fruit before cooling would be the major considerations.

Ripening Centre

RCs receive fruit from different origins and numerous packhouses from around the world. Most of these packhouses would not be willing or able to afford the costs of NIR, so the installation of the NIR at the RC, as the final point of convergence in the supply chain, would theoretically make sense. Furthermore, postharvest diseases and disorders are expressed as fruit ripen, so the NIR would have a greater chance of eliminating fruit at this stage rather than at the packhouse. However, there a practical and economic reasons against this approach.

Significant costs have been incurred by the time fruit are ripened. If fruit were to be scanned before being ripening, the pallets of fruit would need to be broken-down and put over the packline. This additional handling point would add costs, and it is improbable to have a favourable cost:benefit ratio.

There is a rapid diminishing return so that it is not economically viable to remove all of the defective fruit (Table 4), because of the rejection of clean fruit. Supermarkets have extremely stringent quality specifications, so there is a risk that the consignment would still fail inspection even after being sorted by NIR. The RC must determine if the reduced incidence of defective fruit is acceptable to their customers.

A popular phrase in the industry is, "the packhouse (or RC) is not a hospital". It is not economically prudent to add value to poor quality raw product. An RC also does not want to be known to be lax on fruit quality from suppliers. Since only a small percentage of pallets received by a RC have an unacceptably high proportion of defective fruit, it may be more prudent to just not add value to high-risk pallets and avoid investing in NIR technology. The RC would, however, have to perform an economic analysis to be certain of the most cost effective option.

CONCLUSION

Non-destructive testing of avocado maturity using handheld NIR is now possible on a commercial level, with an accuracy comparable to conventional techniques. The measurement of orchard cold (frost) damage, grey pulp (diffuse flesh discolouration), and fruit maturity is possible with online NIR. NIR is not "plug and play" technology and the economic feasibility of integrating NIR into the supply chain is complex and needs to be determined case by case.

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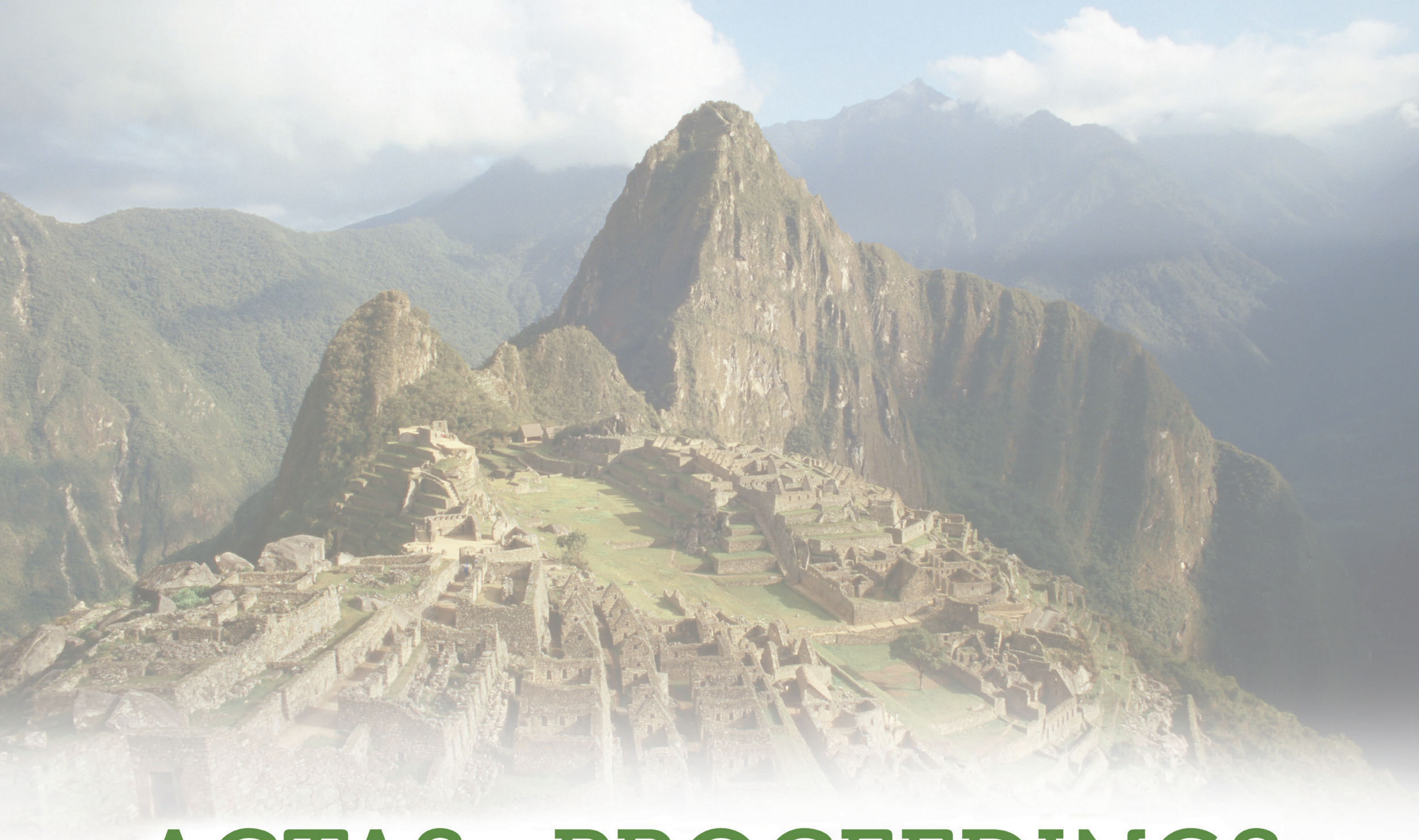

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