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Proximity sensors provide an accurate alternative for measuring maternal pedigree of lambs in Australian sheep flocks under commercial conditions

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Abstract

Context. Proximity sensors were used recently to determine the maternal pedigree of lambs on a small plot with high accuracy. If this accuracy is maintained under commercial grazing conditions, this method could be a useful alternative to improving genetic gain in sheep, including reproduction traits.

Aims. To investigate using proximity sensors to determine the maternal pedigree of lambs and to define the level of interactions required to determine maternal pedigree confidently irrespective of differences in ewe age, lamb age, birth type, paddock size, flock size or stocking rate under commercial grazing conditions.

Methods. We compared maternal pedigree determined using the proximity sensors to DNA profiling (n = 10 flocks) and lambing rounds (n = 16 flocks). Ewes (n = 7315) and lambs (n = 8058) were fitted with proximity sensors under normal grazing conditions for each property for 1–3 days. Flocks varied in ewe age (adults, hoggets and ewe lambs), lamb age (up to 100 days old, except for 1 flock), birth type (singles, multiples), paddock size (0.25–320 ha), flock size (37–420 lambs) and stocking rate (2–100 dry sheep equivalents/ha, except for 1 flock).

Key results. An interaction ratio of >2 was required for a confident ewe–lamb match (ewe with the most interactions compared with the ewe with the second-most interactions for each lamb). Using this criterion, the average success of proximity sensors at matching a lamb to a ewe was 95% and the sensors were 97% accurate when compared with the pedigree results from lambing rounds or DNA. For lambs matched successfully, over 90% of this success was achieved in the first 7 h and over 99% in the first 20 h. While the success rate of matching a lamb to a ewe was not influenced significantly by ewe age, birth type, paddock size, flock size or stocking rate, the time to achieve sensor success was significantly quicker for singles than for twins and sensor accuracy was significantly higher for smaller paddocks with higher stocking rates.

Conclusions. Our results showed that proximity sensors can establish maternal pedigree effectively and accurately across a range of conditions experienced on commercial properties.

Implications. Private industry can now develop more cost-effective sensor technologies with greater confidence that will enhance recording of maternal pedigree and, hence, the rate of genetic gain across the sheep industry.

Keywords: genetics, reproduction, parentage, Bluetooth.

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Introduction

Determining maternal pedigree has benefits for both commercial sheep producers and ram breeders. Ram breeders recording both paternal and maternal pedigree are making the most rapid genetic gain across a range of traits, and this represents a significant opportunity for Merino breeders who record a much higher level of incomplete pedigree (sire only) than do Terminal and Maternal sheep breeders (Brown *et al*. 2006). More rapid gains are possible because determining maternal pedigree improves the accuracy of breeding values and enables the adjustment for maternal effects such as her joining weight, age and birth and rear type. Most importantly, maternal pedigree enables the generation of breeding values for reproduction traits such as number of lambs weaned. Sires with accurate breeding values for number of lambs weaned are difficult to find on our national genetics database (Brown *et al*. 2006) and we estimate that less than 10% of Merino rams are sold with breeding values for reproduction. It is therefore not surprising that there has been marginal genetic gain in the number of lambs weaned from Merino flocks. This is despite commercial producers ranking improving reproduction as the number one priority in their breeding objective (S. N. Hancock and J. P. Trompf, unpubl. data). For a commercial producer, knowledge of maternal pedigree and, hence, a ewe's rearing ability can also enable the culling of non-performers and within-generation improvements in weaning rates (Lee *et al*. 2009). Despite these potential gains in productivity, maternal pedigree is not determined for a majority of commercial producers and ram breeders because current methods are expensive and laborious.

Current methods for establishing maternal pedigree include the conventional tagging and recording of lambs to ewes during lambing (Kennedy and Bettenay 1950), matching ewes to their lambs in pens pre-marking (Smith *et al*. 1966), setting up pedigree matchmaker (Richards *et al*. 2007) and measuring DNA parentage from blood samples (Dodds *et al*. 2005). DNA parentage is the most accurate method to determine pedigree, but it is more expensive than is conventional mothering up and pedigree matchmaker (Van der Werf 2010). Pedigree matchmaker determines the maternal pedigree of lambs through association with dams when they pass a fixed point in the paddock and can achieve 90–96% accuracy when data are collected for more than a month (Richards and Atkins 2007). The development of sensors and accompanying software have created new opportunities to measure novel traits, including dam pedigree, more quickly than with pedigree matchmaker, but there has been limited testing of their robustness and accuracy at commercial scale.

Time of oestrus, for example, has been successfully detected using sensors, by measuring the interactions between males and females (O'Neill *et al*. 2014; Alhamada *et al*. 2016, 2017; Paganoni *et al*. 2020). Measuring the interactions between ewes and lambs with sensors has also been used to determine the maternal pedigree of 23 twin-born lambs with 100% accuracy after 15 min (Sohi *et al*. 2017). Maternal pedigree was obvious in Sohi *et al*. (2017) as twin lambs that were up to 3 weeks old interacted three times more with their maternal ewe than with other ewes. Given that ewes and their newborn lambs do not appear to interact differently with other ewes in large or small flocks (Lockwood *et al*. 2019), it is likely that using proximity sensors on larger commercial flocks should be equally successful at determining maternal pedigree. However, it is possible that the number of interactions between lambs and their dams may decrease as the lambs get older and become more independent (Morgan and Arnold 1974), or may differ between single- and multiple-born lambs (Walser *et al*. 1983). Nevertheless, there is still likely to be a minimum ratio that can be determined with confidence for all lambs for the purpose of maternal pedigree by using proximity sensors.

The major aim of the present study was therefore to determine an appropriate ratio of interactions that can determine the maternal pedigree of lambs confidently, irrespective of age, birth type, different stocking rates, flock or paddock sizes using proximity sensors. We hypothesised that proximity sensors would determine maternal pedigree under larger commercial-scale flocks accurately and rapidly, irrespective of variations in age, birth type, stocking rate, flock or paddock sizes.

Materials and methods

All procedures reported in the present paper were conducted according to the guidelines of the Australian Code of Practice for the Use of Animals for Scientific purposes and received approval from the Animal Ethics Committee of the Western Australian Department of Primary Industries and Regional Development.

Sites

Proximity sensors were fitted to ewes (n = 7315) and lambs (n = 8058) during 2016 and 2017, across 40 flocks from 21 properties. There were known problems with methodology at three properties, which were consequently removed from the analysis. One property was removed because it was the only site where sensors were put on half the flock. Therefore, many dams in the flock did not have collars and this could have contributed to lower results. The other two properties (with 7 flocks) were excluded because the sensors were on the sheep for less than 1.5 days (15–25 h), while all other properties had the sensors on for a minimum of 36 h. After excluding these three properties, there were 32 flocks across 18 properties remaining for inclusion in the analyses, with a total of 6747 lambs (Table 1).

The properties were located in Western Australia (14 properties), Victoria (3 properties) and New South Wales (1 property). Fifteen of these properties (27 flocks) were Merino flocks, while the remaining three properties were Dorper (1 flock) or composite maternals (4 flocks). One-third of lambs (n = 2215) were from research flocks in Western Australia, including 1681 lambs from the Breech-strike Resource flock at Katanning (Greeff and Karrlson 2020, 394 lambs from the Merino Lifetime Productivity flock at Pingelly (Clarke *et al*. 2019) and 140 lambs from the Whitby flock at Serpentine (Inglis *et al*. 2019), representing properties C, L and K respectively in Table 1. The remaining lambs (n = 4532) were from commercial ram-breeding properties that volunteered to participate in the study.

Flock size varied from 37 to 420 lambs across properties, paddock size varied from 0.25 to 320 ha and stocking rate varied from 2 to 100 DSE/ha, except for one research site (Flock K) with a higher stocking rate (Inglis *et al*. 2019).

Maternal pedigree

Maternal pedigree was collected on-farm by one or more of the following four methods: (i) pedigree matchmaker (PMM) (ii) mothering up in pens; (iii) mothering up at birth; and (iv) DNA analysis. For the properties that performed mothering up at birth, twice-daily lambing rounds were performed. For the properties that performed mothering up in pens, suckling determined a successful match. For the DNA analysis, blood cards were collected at marking, weaning or early post-weaning and submitted to Sheep Genetics

Table 1. Summary of sensor success and accuracy results by flock together with flock size, farm pedigree method, stocking rate, average lambing age, state and breed

Flock	No. of lambs	Sensor success (%)	Pedigree method	Sensor accuracy (%)	Stocking rate	Average lamb age (days)	State	Breed
A1	91	97	Birth	97	20	13	WA	Merino
A2	201	98	Birth	97	36	13	WA	Merino
B1	165	95	Birth	98	99	48	Vic	Merino
B2	96	96	Birth	100	65	36	Vic	Merino
B3	36	81	Birth	100	66	36	Vic	Merino
C1	161	98	Birth and DNA	99, 99		44	WA	Merino
C2	146	97	Birth and DNA	96, 98		44	WA	Merino
C3	398	98	Birth and DNA	98, 97		77	WA	Merino
C4	318	96	Birth and DNA	97, 97		71	WA	Merino
C5	331	96	Birth and DNA	97, 97		75	WA	Merino
C6	327	95	Birth and DNA	96, 95		77	WA	Merino
D1	221	96	DNA	98	25		WA	Merino
D2	321	98	DNA	97	29		WA	Merino
E	283	95	Yard		2		NSW	Merino
F	253	81	None		18	95	WA	Merino
G	225	96	DNA	94	12		WA	Merino
H1	141	99	Birth	94	28	22	WA	Composite
H2	177	95	Birth	95	17	17	WA	Composite
I1	267	94	None		24		WA	Composite
I2	101	98	None		14		WA	Composite
J	107	79	None		4		WA	Dorper
K	140	96	Birth	100	369	54	WA	Merino
L	394	95	DNA	95			WA	Merino
M	340	97	None		37		WA	Merino
N1	167	96	PMM		7		WA	Merino
N2	112	92	PMM		3		WA	Merino
O	184	97	PMM		6		WA	Merino
P1	84	95	Birth	96	10		Vic	Merino
P2	133	99	Birth	96	30		Vic	Merino
Q	420	92	PMM		61		Vic	Merino
R1	160	93	None		16		WA	Merino
R2	247	95	None		11		WA	Merino

(sheepgenetics.org.au) for analysis, and then provided to us by the producers. DNA samples were collected using various methods among properties, including tail blood at marking, direct blood sampling from the jugular, or by taking a blood or tissue sample from the ear. Five properties failed to collect or provide any on-farm pedigree data, affecting about one fifth of lambs measured (n = 1475). These lambs could be used for analysis of sensor success, but not analysis of sensor accuracy.

Sensors

Bluetooth was used to measure proximity as this technology is cheaper, consumes less power than do other wireless technologies and has been commercialised in Australia. We used ActiGraph GT3X sensors (v. 4.4.0 Pensacola, Florida, USA), a flagship activity monitor for research; however, only their Bluetooth function was relevant for the study. Ewes were fitted with beacons (emitting a signal) and lambs were fitted with receivers (receiving signals).

A minimum period of 2 days of interaction data was recorded for each sheep at most sites. Interactions between ewes and lambs were counted using proximity sensors via Bluetooth at 30 hz over a 1–15 m range. Interactions were counted via Bluetooth every minute (e.g. 10 min within range equals 10 interactions) within this 1–15 m range, with a maximum of 10 different beacons per receiver per minute being recorded. The sensors were wrapped in silicon tape and tied with cable ties to dog collars that were fitted to the sheep in a handling race. Unique electronic identification numbers on the collars were paired with the matching electronic identification number on the animal ear tag by using an XRS2 TruTest stick reader (Datamars, Banyo, Queensland, Australia). Pairing of tags to collars was performed at the time of collar fitting and again at removal. Less than 1% of all sensors (148 of the 15 373 sensors fitted) failed or were lost at removal. Ewes and lambs were managed under normal farm and grazing conditions while wearing the collars.

The data were extracted from the sensors by using ActiLife software after removal. Only the data from the receivers were used. The receiver records a signal strength for each beacon within range (for a maximum of up to 10 beacons). This signal strength was first converted to binary code and then a series of macros summed the total interactions for each lamb for the relevant analysis. The protocols for using ActiGraphs for this purpose were developed by Sohi *et al*. (2017).

Sensor success and accuracy

The ewe with the most interactions with each lamb was identified as the first dam. The ewe with the second-most interactions for each lamb was identified as the second dam. A minimum ratio of interactions between the first and second dam was used to determine a successful match of lamb to ewe.

To calculate the accuracy of the sensors, the match achieved by the sensor was compared with the match achieved by DNA or mothering up, as these two methods are considered to be more accurate than is pedigree matchmaker. Twenty flocks had on-farm pedigree results collected by mothering up at birth and/or DNA analysis, with a total of 4106 lambs.

The success of the sensors at matching ewes to lambs was categorised as high or low. The minimum ratio that achieved 90% accuracy between the sensor and the DNA or mothering up was categorised as a 'high confidence' or successful match. The interaction ratios that achieved <90% accuracy between the sensor and DNA were categorised as 'low confidence' or not successful matches.

Statistical analyses

To analyse the effectiveness (success) of the sensors, we compared with a Student's *t*-test the percentage of lambs matched successfully to a ewe by the sensors with the percentage of lambs matched to a ewe by various on-farm pedigree methods.

Regression and Student's *t*-tests were used to analyse the relationship between both the effectiveness and accuracy of the sensors against birth type, lamb age, stocking rate, paddock size, flock size and ewe breed. Statistical significance was determined typically from analysis of flock means. The paired Student's *t*-test analysis of birth type (singles verses twins) was restricted to flocks where singles and twins each represented over 10% of the lambs (n = 27 flocks for sensor success and n = 15 for sensor accuracy). The time taken to reach sensor success was also compared between singles and twins.

While ewe breed and birth type were available across all flocks, average lamb age was available for 15 flocks, ewe age for 13 flocks and paddock size for 25 flocks (Table 1). Stocking rate for these 25 flocks was calculated using a 50 kg dry sheep equivalent (DSE) for non-lactating ewes, a lactating ewe with one lamb being 2.5 DSE and a lactating ewe with twins being 3.4 DSE (adapted from McLaren 1997). Ewes with more than two lambs were calculated as per twins (3.4 DSE).

Results

Confidence parameters – interaction ratio

Sensor success required an interaction ratio of >2 (the ewe with most lamb interactions compared with the ewe with second-most lamb interactions). Table 2 shows the proportion of matches where the ewe identified by the sensor matches the ewe identified by the farm pedigree method, achieved with different ranges of the ratio. The calculation was based on the lambs that had a ewe determined by both sensors and either DNA or matching up at birth (3958 lambs across 20 flocks). The lambs with an interaction ratio of >2 were categorised as 'high-confidence' matches and this was achieved for 97.5% of lambs matched. The accuracy of these high-confidence matches was 96.7%. Lambs with interaction ratios of <2 were categorised as 'low-confidence' matches. There is also little sensitivity to the choice of criteria because so few lambs had low interaction ratios (only 2.5% of lambs matched had interaction ratios of <2).

Table 2. The effect of the interaction ratio on accuracy of matches using 3958 lambs from 20 flocks where DNA or mothering up at birth were used to confirm sensor accuracy (sensor = farm pedigree)

Interaction ratio	Accuracy of matches (%)	Number of lambs (% in parentheses)
1–1.5	30	60 (2)
1.5–2	74	39 (1)
2–3	91	155 (4)
>3	97	3704 (94)

Accuracy of sensors

The average accuracy of the sensors was 97% across 20 flocks, with DNA and/or mothering up at birth as the farm pedigree method. The calculation was based on the 3859 lambs with both sensor success and farm maternal pedigree, which was 94% of the lambs in these flocks. There was no farm pedigree data for the remaining 12 flocks. The accuracy when comparing sensors with birth (16 flocks) or DNA (10 flocks) was always 94% or higher (Table 1).

One Merino research property (Property C) had DNA, mothering up and 1681 lambs fitted with sensors. Mothering up failed to give a result for 13 of these lambs (0.8%). DNA failed to give a result for 77 of the lambs (4.6%). The sensors failed to give a result for 50 of the lambs (3.0%). Compared with DNA, the mothering up gave 36 (2.1%) and the sensors gave 50 (3.0%) different dam results. For 16 lambs, the mothering up and the sensor results were the same, but the DNA result was different (1.0%).

Effectiveness of sensors

The average success rate of the sensors in identifying a lamb to ewe was 94.5% (n = 32 flocks), which ranked it similar to DNA (94.4%; 10 flocks), significantly above pedigree matchmaker (90.2%, 4 flocks; $P < 0.1$) but below mothering up at birth (97.8%, 16 flocks; $P < 0.05$). The average success of proximity sensors increases to 95.8% if calculated as an average of the 20 flocks that had results for mothering up at birth or DNA.

Time to achieve sensor success

For lambs with a successful ewe match, 99% of the matches were identified in the first 20 h (Fig. 1). Over 90% of successful matches were achieved after 7 h and 95% after 11 h.

Lamb age

Sensor success did not decline for lambs up to age 80 days in age (Fig. 2). All flocks had age ranges of less than 50 days and no lambs of age >100 days except for Flock F. Flock F had lambs from age 2 days to 206 days. The majority of Flock F lambs were between 80 and 125 days, with an average sensor

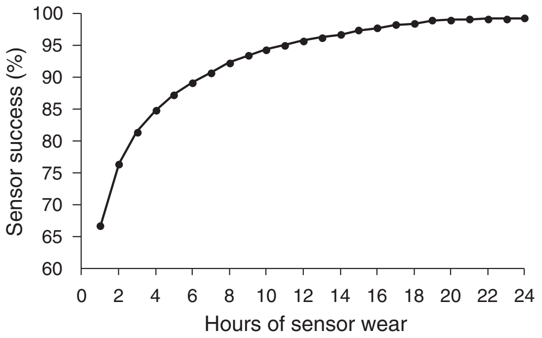

Fig. 1. The success over time of proximity sensors in matching a lamb to a ewe across 32 flocks (n = 6409 lambs) for those lambs that were successfully matched (interaction ratio of >2).

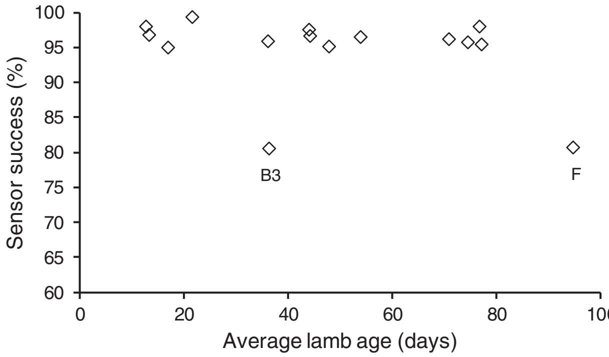

Fig. 2. The relationship between lamb age and the success of proximity sensors in matching lambs to ewes. The data are from 15 flocks (n = 2983 lambs). The low success of Flock B3 and Flock F is discussed in the text.

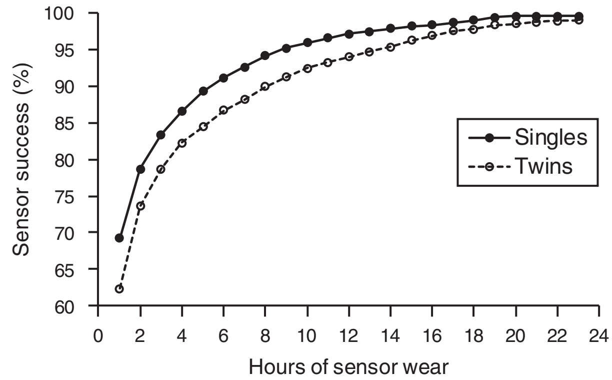

Fig. 3. The success over time of proximity sensors in matching single- and twin-reared lambs for those lambs that were successfully matched (interaction ratio of >2). The data are from 27 flocks (n = 2623 singles, n = 3004 twins). The difference is highly significant at 1, 5, 10 and 15 h ($P < 0.001$) and remains significant at 20 and 24 h ($P < 0.05$).

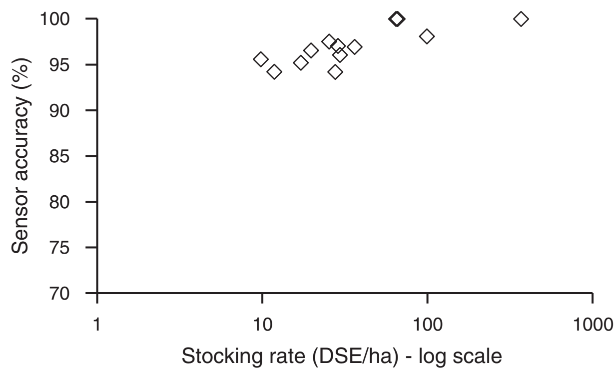

Fig. 4. The relationship between stocking rate (dry sheep equivalents/ha) and the accuracy of proximity sensors for those lambs that were successfully matched to a dam. The results are from the 13 flocks with both stocking rate and sensor accuracy information.

success of 87%. For the group of 29 lambs with age of >125 days, the sensor success was much lower at 38%. The smallest flock, Flock B3, was the only other flock with sensor success of <90%, having seven lambs with an interaction ratio of between 1.4 and 2.0. A lower interaction ratio of 1.4 would have improved sensor success to 100% for this flock.

Rear type

There was no significant difference in sensor success between singles (95.5%) and twins (95.2%). Sensor accuracy was also not significantly different between singles (98.2%) and twins (97.5%). There were limited triplets having lower sensor success (77.0%, 183 lambs) and accuracy (91.5%, 94 lambs).

The time to achieve a successful match was also compared between singles and twins for this dataset and a successful match took significantly longer with twins (Fig. 3). The difference was highly significant up to 15 h ($P < 0.001$) and remained significant at 24 h ($P < 0.05$). While 95% of successful matches were achieved after 9 h for singles, this took 14 h for twins.

Ewe age

For 13 of the flocks, ewe ages were recorded. For each year from 2010 to 2015, there were >10 ewes for several sites. While sensor success appeared to be lower for the youngest ewes (born in 2015), the difference was not significant.

Flock size, paddock size and stocking rate

There were no detectable effects of flock size, paddock size or stocking rate on the success of the sensors; however, there was a significant increase in sensor accuracy (99% vs 96%) for sites with higher stocking rates and lower paddock sizes (Fig. 4).

Ewe breed

Sensor success was low (79%) for the one dorper flock but did not differ significantly between Merino and non-Merino ewes. Sensor accuracy was lower for non-Merino ewes but this was based on limited data as only one site of composite maternal ewes had mothering up data to calculate sensor accuracy.

Discussion

Proximity sensors were observed to be robust compared with other methods of maternal assignment across a range of conditions experienced on commercial properties across southern Australia. An interaction ratio of >2 matched lambs to ewes with 96.7% accuracy compared with DNA or mothering up. Proximity sensors matched 94.5% of lambs to ewes, indicating that the sensors were successful. We therefore conclude that proximity sensors can determine maternal pedigree with success and accuracy equal to those of DNA, which is considered currently the most reliable method to determine maternal pedigree.

An interaction ratio of 2 matched a ewe to a lamb with high confidence. This was lower than the ratio of 3 reported by Sohi *et al*. (2017); however, we compared the ewe with the highest number of interactions to the ewe with the second-highest number of interactions for each lamb, whereas Sohi *et al*. (2017) compared the ewe with the highest number of interactions for each lamb to the average number of interactions each lamb had with any other ewe in the flock. The latter method is valid for smaller flock sizes or paddocks where between-ewe interactions are higher (Lockwood *et al*. 2019). However, in larger flocks and paddocks, the probability of each ewe and lamb interacting is lower and this method could be less reliable. Comparing the ewe with the most interactions with the ewe with the second-most interactions will give a confident ewe–lamb match irrespective of flock or paddock size, demographics or grazing behaviours.

A confident ewe–lamb match was achieved after 20 h of wearing the proximity sensors. Across all 32 flocks, the success of proximity sensors in matching a lamb to an ewe was 90% after 7 h of wear time, increasing to 95% after 11 h and to 99% after 20 h of wear time, indicating the rapid re-establishment of the ewe–lamb bond following mustering and fitting of the sensors. Sohi *et al*. (2017) established that this period could be as short as 15 min in flocks with fewer than 25 lambs. The significance of this finding is that it allows proximity sensors to be re-used either within a defined battery life or at least within a lambing season, hence reducing the cost of devices per animal.

As importantly, flock demographics did not affect sensor success in matching lambs to ewes. There was no convincing evidence that ewe age, lamb birth type, paddock size, mob size, stocking rate or lamb age up to 80 days influenced the success of the sensors, although there was a significant effect of stocking rate on sensor accuracy. Sohi *et al*. (2017) reported a lower frequency of ewe–lamb interactions for 3-week-old lambs than for 1- and 2-week-old lambs, which was consistent with previous reports that an ewe's interactions with her lambs decline with an increasing age of the lamb (Dwyer 2014). If these changes in ewe–lamb interactions exist, they were of little practical significance as maximum success was still achieved within 24 h regardless of lamb age up 80 days of age. This is consistent with observations that organic matter consumption from grass increases to 50–60% of a lamb's diet between 60 and 70 days old (Langlands and Donald 1975). Only one site had lambs older than 100 days and sensor success declined to 38% for lambs older than 125 days, suggesting that older lambs may have begun self-weaning, decreasing the time spent with their dam and therefore did not return accurate results. This potential decline in success of proximity sensors in older lambs does not limit their application commercially as lambs are weaned typically before they are 100 days old.

Mothering up at birth and DNA testing cost more than do commercial proximity sensors, but mothering up gives birthweight and date information and DNA can be measured from dead lambs and gives extra genomic information. There are likely to be other advantages in using proximity sensors that are yet to be discovered, such as indicators of mothering ability, milk production and growth rates. For all pedigree methods, errors are introduced through mis-recording sheep IDs, failing to measure all sheep (e.g. failed blood cards, not sampling/applying collars to all sheep), mismothering at or shortly after birth, and challenges in working with novel technology. In one Merino research flock where three pedigree methods were used (DNA, mothering up and sensors), mismothering appeared to affect ~1% of lambs and sampling failures affected results for ~5% of lambs. Ultimately, the accuracy of each method will be determined by the effort and success in reducing these errors. The most appropriate pedigree method will most likely depend on the objectives of individual producers, and their ability to provide the necessary labour requirements and/or funds. Nevertheless, using proximity sensors appears to be a promising alternative that may have other practical applications.

Conclusions

Proximity sensors provide a rapid and accurate method for establishing maternal pedigree that is comparable to existing methods of mothering lambs to ewes and blood sampling for DNA. Comparing the lamb and ewe with the most interactions with the lamb and ewe with the second-most interactions at ratios above two gives a confident ewe–lamb match irrespective of flock demographics or paddock size.

Conflicts of interest

The authors declare no conflicts of interest.

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