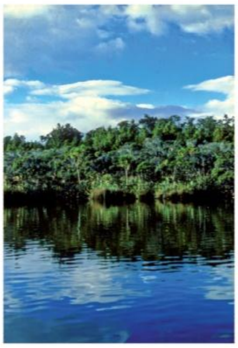

Remote monitoring of traps using wireless-based systems

Landcare Research
Manaaki Whenua

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Additional comments?

Contents

Summary

Project and Client

Over recent years there has been an increasing number of vertebrate pest control programmes using permanent networks of traps to maintain pest numbers at low levels, and in parallel, a growing interest in the potential of wireless systems for remote monitoring of these networks to minimise the time and cost associated with checking traps. The Hawke's Bay Regional Council (HBRC) contracted Landcare Research to review the potential and economics of using wireless networks for monitoring a kill-trap network. The report fulfils Landcare Research's 2014/2015 contracted Milestone 2.5 with Hawke's Bay Regional Council.

Objectives

- Review the wireless trial results (to be conducted Feb/March 2015) from the perspective of operational delivery of wireless technology into the field, and analyse the ability of wireless technology to reduce operational costs (30 June 2015). Note the first part of this objective has not been possible because of timing of wireless technology development and testing.

Findings

- A range of commercially available wireless sensor network (WSN) systems is available, with most running on 2.4 GHz frequency.
- A high frequency, such as 2.4 GHz, has limited range in undulating topography and through dense vegetation.
- The lower frequency of 160 MHz, like 2.4 GHz, is freely available if used below a specified power output, but because of its greater range across undulating topography and through dense vegetation it is more suitable for use in spoke and hub network configurations.
- There are two main types of network configurations: (1) mesh-networks (including lines or chain configurations), and (2) hub and spoke networks.
- When selecting a WSN, node capability, transmission frequency, method for uploading data from the network, and network configuration need to be taken into account.
- There are three main reasons for checking traps: (1) legal requirements, (2) trap saturation, and (3) bait replacement. Each of these factors will impact on the benefit-to-cost ratio of using a WSN.
- For both live- and kill-trap networks, significant benefit-to-cost ratios can be obtained, but these depend particularly on the price of the technology but also on other parameter values used.
- If it is too expensive to monitor every trap in a network, a subset of traps could be monitored to assess when the proportion of traps sprung has met a pre-determined trigger level. The number of traps monitored depends on the precision required, but is likely to be 200–250 traps for a network of 500 or more traps.

Conclusions

- The integration of WSN into large-scale permanent trap networks has the potential to deliver significant savings through the reduction in trap checking time.
- Economic models of both live-trap and kill-trap systems show that WSN monitoring can result in positive and significant benefit-to-cost ratios, with the correct mix of factors.
- The extent of the savings when using WSNs will depend on the scale of the networks (the larger the network, the larger the benefits), the availability of long-life bait (the longer the bait life the greater the benefits), and the capture rate (the lower the capture rate and time for traps to fill, the greater the benefit).
- Additional benefits will accrue if volunteers (farmers/community groups) are used for checking sprung traps.
- If long-life baits become available, ideally every trap would be monitored, so a responder (trap checker) would have to check only those traps that have sprung.
- If, because of cost, only a subset of traps can be monitored to determine when to check the whole trap network, about 250 traps need to be monitored (number will depend on precision required). However, as the trap network increases in size the benefit-to-cost ratio will increase when using this number of monitored traps.

Recommendations

- Field trials continue to test available WSNs so data can be obtained on the technology costs and the savings gained through reductions in trap network servicing costs.
- Systems tested use 160 MHz rather than 2.4 GHz.
- Any roll-out of WSN technology is based on prior economic analyses, at least to obtain some basic understanding of the likely benefit-to-cost ratio.
- Initial tests are based on a subset of traps to monitor only the proportion of traps sprung. Once confidence is gained with the technology, it should be rolled out across a full trap network with a mix of possible trap responders (checkers) involved. This would enable the use of WSN monitored trap networks to be optimised and the benefit-to-cost ratio maximised.
- The economic models be further developed to capture the full range of possible WSN scenarios influenced by HBRC selected policy and practice.

1 Introduction

Over recent years there has been an increasing number of vertebrate pest control programmes using permanent networks of traps to maintain pest numbers at low levels. At such low densities of pests, few traps are sprung, and staff or contractors often spend more time checking traps that are still set than dealing with captures. Consequently, there has been a growing interest in the potential of wireless systems for remote monitoring of traps to minimise the time and cost associated with checking them. The Hawke's Bay Regional Council (HBRC) contracted Landcare Research to review the potential and economics of using wireless networks for monitoring a kill-trap network. The report fulfils Landcare Research's 2014/2015 contracted Milestone 2.5 with Hawke's Bay Regional Council.

2 Background

Vertebrate pest control in New Zealand has been evolving over the last decade from a paradigm of control applied periodically with intervening periods of no control, to a paradigm of essentially continuous control so pest numbers are maintained at low levels (presumably below some threshold at which desired values are protected). There has also been a desire to increase the scale of control programmes, with some now covering hundreds of thousands of hectares. This evolution of control programmes has seen the increasing use of permanent networks of live- and kill-traps with a wide range of setting and checking regimes employed. However, irrespective of the implementation details, a common outcome is that pest numbers are held at low density and, especially when having to check live-capture traps daily, the majority of traps checked have no captures. Once a trap network is established (i.e. the initial capital cost is committed), the main cost of running a network is staff or contractor time to check the traps. Current management questions are: can this staff or contractor time be reduced by using wireless monitoring, and do the subsequent operational cost savings justify the expenditure on a wireless network?

Wireless systems have been developed recently to enable a wide range of environmental sensors to be monitored remotely and, if required, in real or close-to-real time. This report reviews current environmental monitoring wireless technology, discusses the potential trapping regimes that may benefit from being remotely monitored (i.e. operational delivery of wireless solutions), and describes an economic model for assessing the value of remote monitoring of a kill-trap network.

3 Objectives

Review the wireless trial results (to be conducted Feb/March 2015) from the perspective of operational delivery of wireless technology into the field, and analyse of the ability of wireless technology to reduce operational costs (30 June 2015). Note the first part of this objective has not been possible because of timing of wireless technology development and testing.

4 Findings

4.1 Wireless technology

4.1.1 Historical systems

Since the early 1980s, remote monitoring of traps and other detection devices has been investigated to determine how it might minimise both programme costs (Gebhardt et al. 2009) and the time for which animals are held captive (Larkin et al. 2003). Early efforts used trip-switches to activate, deactivate, or change the pulse rate of modified very-high-frequency (VHF) telemetry transmitters when a trap or other device was triggered (Hayes 1982, Nolan et al.1984, Marks 1996). Subsequent developments included the use of mobile-phone-based applications for more remote and real-time monitoring (Larkin et al. 2003).

Since then, there has been a natural progression from use of single relay stations passing on data from an array of devices to the use of multiple relay points, each with its own detection array. This is, essentially, the concept behind wireless sensor networks (WSNs). A WSN consists of devices that detect and measure environmental variables (the sensors), and a way for those sensors to communicate data to each other and/or back to a base station wirelessly.

4.1.2 Current systems

Digi International is one of the leading companies in the world making wireless radio modules and gateway systems (http://www.digi.com/) for establishing wireless sensor networks (WSN). Their radio modules are built on two wireless protocols (i.e. international standard Zigbee and proprietary Digimesh). Both use 2.4GHz frequency, which falls under a licence-free frequency band in New Zealand. Their mesh networking wireless systems, which are based on Digimesh, have been widely used for environmental monitoring (Hedley et al. 2010, Delamo 2015). These mesh networks are self-organising and self-healing, making them ideal for monitoring environmental parameters in real time. They require minimum maintenance as they can self-recover from individual node failure. Digi International systems also provide the facility for two-way communication, which can be useful, for example for monitoring a device as well as remotely controlling any switches at the device (e.g. opening a bait station door). Additionally, their cloud-based data storage makes it easy for end users to manage the data online without investing heavily in their own data retrieval and storage system.

Memsic (formerly Crossbow) is another manufacturer who uses its own proprietary protocol of mesh networking wireless sensor network systems for environmental monitoring (http://www.memsic.com/). Indigo wireless systems, based in New Zealand, also provide mesh networks for environmental monitoring (http://www.indigosystems.net.nz/meshnetworks.html). Their systems are commonly used for soil water monitoring in New Zealand and Australia. Both of these systems use the 2.4GHz frequency.

The systems vary in configuration, node capability, transmission frequency used, and method of transmission from the network to the ‘office’ (i.e. the place and system where the data are stored and queried, and/or the relevant person alerted).

Configuration

There are two main types of network configurations: (1) mesh-networks (including line or chain configurations), and (2) hub and spoke networks. Mesh networks comprise multiple nodes (i.e. a sensor that can communicate with one or more neighbouring nodes) and one or more base stations or ‘gateways’ that send data from the network to the office (Szewczyk et al. 2004). The ability of nodes to communicate with each other enables mesh networks to be self-organising and self-healing. That is, if one node fails an alternative data transfer pathway can be used involving other neighbouring nodes. Additionally, because data are transferred through the network each node does not have to be able to communicate with the base stations. All sensor nodes in a mesh network can be programmed to wake up in unison for a few seconds and go back to sleep for pre-set time periods, but generally less than a day. The sleep time period could be from a few seconds to many hours, which helps to conserve battery power. More simple networks can be configured as chains (e.g. along a trap line), but such a configurations might limit the self-healing ability of the network unless each node can skip an adjacent malfunctioning node or communicate in both directions along the chain, if there were base stations at both ends.

Hub and spoke networks, which are commonly built on Zigbee protocols, rely on each node (commonly called end nodes) communicating directly with a base station at the hub rather than communicating via a network of neighbouring nodes. The main limitation on the use of these systems is the distance over which the node can transfer data to the hub, which is most influenced by the transmission frequency used. However, hub and spoke networks may have very low power requirements, because they can sleep for long time periods without waking up to send data to the base station (which does stay awake). Although mesh network nodes can also sleep, they must wake up regularly (at least once a day) to ensure the time in each node stays synchronised. Nodes in hub and spoke network systems, like mesh network systems, can relay data to the base station using other specially configured nodes as routers. Unfortunately, routers cannot sleep so use of them in remote monitoring systems is difficult without solar power back up or mains power.

Node capability

Each node has a sensor designed to monitor a parameter or set of parameters (in this case the status of a trap) and either store the resulting data or transfer them onwards to a base station. The capability of each node will depend on the system requirements (e.g. close-to-real-time monitoring or data storage until a pre-programmed communication time). Each wireless senor node may have its own programmed intelligence to make decisions based on its inputs (e.g. capture, sprung but empty, still set). Some custom-made sensor nodes have the ability to store all measured parameters in the on-board memory for later retrieval in case of sensor network malfunction.

Transmission frequency

The radio frequencies available for use in sensor networks are restricted by licencing. According to the NZ government radio spectrum management site (http://www.rsm.govt.nz/about-rsm/who-is-radio-spectrum-management), the commonly used 2.4 GHz frequency is free to use providing the maximum antennae output power does

not exceed 1 watt. The higher frequencies such as 2.4GHz has been adopted by most commercial network manufacturers because this and higher frequencies have a lower risk less risk of data corruption when information is being transmitted. A frequency used for radio tracking animals in New Zealand (160 MHz) is also freely available, but has lower output restrictions than 2.4 GHz. Apart from licencing restrictions, the selection of frequencies is most influenced by their ability to transmit across undulating topography and/or through dense vegetation. As a general rule, the higher the frequency the more direct line of sight required (Chen et al. 2001). Depending on the transmission power, using di-pole antennas 2.4GHz will generally require nodes to be less than 200 m apart in flat and open areas, but perhaps less than 50 m apart in dense vegetation. However, low power (40mW) 2.4GHz radio modules with Yagi Antennas could communicate over 8Km (Line-of-Sight). In contrast, using 160 MHz enables nodes often over 500 m apart to communicate with a base station even in dense vegetation or over undulating topography.

For a hub and spoke system that does not use intermediary nodes, 160 MHz will be more effective than 2.4 GHz. There is a fine balance between the radio transmission power, operating range and practicability. If permitted by the law, it is obvious that higher power will achieve longer transmission distance for both high and low frequencies, but will require larger energy sources (i.e. larger and more expensive batteries).

Uploading data from the network

There are several options for uploading data from networks, including:

1. visiting the base station and uploading the data through hardwire or wireless connection.

2. semi-remote upload, by receiving data from each node, by being in close proximity to or within the network.

3. remote upload, by the base station transmitting data to the office periodically, using either the cellular network (if coverage enables it) or satellite transmission. The systems can be programmed to text or email data to ensure those responsible for the network are updated on the status of each node. The frequency and timing of such data uploading will depend on the system requirements (i.e. for live traps uploading might be required daily, but for kill trap networks weekly might be sufficient). Digi International provides their own cloud-based data storage to store data uploaded from the sensor networks (at no extra cost).

4.2 Trap scenarios

Both live- and kill-traps are set and checked in a wide range of scenarios, and the addition of remote monitoring using wireless systems will generate few economic benefits for some scenarios and potentially large benefits for others. Rather than assume that the adoption of wireless technology will automatically provide significant savings to a pest control programme, managers of such programmes need to be aware of the range of possible scenarios in which wireless systems could be used, and if possible, carry out an economic analysis of any proposed system.

There are three main reasons for traps to be checked: (1) legal requirements, (2) trap saturation, and (3) bait replacement.

1. *Legal requirements:* The Animal Welfare Act 1999 – S32 requires all live traps to be inspected within 12 hours after sunrise on each day the trap remains set. Consequently, irrespective of whether these traps have captured or not, they must be checked daily and this requirement imposes a high operational cost. Discussions are being held between Zero Invasive Predators Ltd (ZIP) and MPI Animal Welfare Group to clarify what would be legally accepted as an 'inspection' in a wireless monitoring system , and the required level of redundancy in the system to ensure it is fail-safe.

2. *Trap saturation:* When the proportion of traps sprung is greater than approximately 20%, the unavailability of these traps has an impact on the overall capture rate of the network, i.e. the network starts to become saturated (Caughley 1977). Consequently, if target or non-target densities are high, frequent trap checking will be required to prevent this.

3. *Bait replacement:* If bait does not have a long field life, all traps will need to be visited frequently to keep bait attractive. Additionally, bait replenishment will also be required if non-target species remove bait.

4.2.1 Live-trap systems

Live traps include leghold, cage/box, or treadle traps, and all of these must be inspected daily. If remote monitoring enables the person responsible for the trap network (*viz.* trapper) to inspect only those traps that have been sprung, then the quantum of savings will depend on the percentage of traps sprung and how efficiently those sprung traps can be checked. This efficiency will depend, in turn, on how each trap can be accessed. That is, if traps can only be accessed along a line (e.g. up a forest ridge) then, if the last traps in the line are sprung all traps have to be walked past even if they are still set; consequently there would be little saving. However, even in this scenario, if only the first few traps were sprung then the rest of the line would not have to be checked and significant savings might be obtained. If traps were set across a farmland/bush habitat mosaic with multiple access points, there would be greater opportunity to capitalise on knowing which traps were sprung and spend time checking only those. In all scenarios, it is important to recognise the difference between potential savings and realised savings. That is, a trapper, by using a WSN might have a potential saving of 4 hours of checking time, but because they do not have other funded activities on which they can use the saved time, they might still need to charge the full day to the job and therefore not realise the savings. Hopefully over time, if the savings in time were consistent, then the trapper could plan to run a larger network of traps thereby realising the full savings.

To assess the potential operational cost savings from using a WSN for monitoring live-capture traps, Jones et al (2015) used a simple deterministic spreadsheet model. They estimated the relative operational costs for two sizes of live-trapping networks (150 and 300 traps) under 3 scenarios: 1) daily visits to every trap by a trapper; 2) visits to only those traps detected as sprung by a WSN; and 3) use of a WSN, but with a forced 5-day interval rebaiting and servicing schedule (i.e. when all traps need to be visited and rebaited). The operational costs included a trapper's travel (i.e. time and vehicle costs) from a base to the

start of a trapping network, and around the network by vehicle to check each trap daily for 10 consecutive days every month. Sprung traps incurred a greater time cost to check than unsprung traps because of the need to process trapped animals or to reset sprung, but empty traps. At the end of the network, the trapper travelled back to base. To simulate a realistic distribution of daily numbers of sprung and unsprung traps in the network, they used a random integer-selection function constrained so that simulated 10-day sprung trap rates closely matched the mean monthly trap-rates from a real-world predator trapping programme in the South Island, where traps were set for 10 days every month (Department of Conservation, unpublished data, 2006–2011).

Additional assumptions included: (1) a 20-km drive from the base to the start of the network took 15 min, (2) the drive around the network was 15 km long for the 150-trap network and twice that for the larger network, (3) the trapper could travel at 8 km/hr around the network by off-road vehicle, (4) the time taken to check each trap was 1 or 6 min for unsprung and sprung traps, respectively, (5) the labour rate was $20.00/hr, and (6) the vehicle running cost was $0.75/km.

Thus total cost is:

$$Cost_{total} = S + 2T_0 + T_n + C_u + C_s$$

where: S = set-up costs at base = $S_h \times w$, given a set-up time (S_h hr) and an hourly labour rate (w). T_0 = travel cost between base and start of network = $[B_t \times W] + [B_d \times V]$, where B_t = travel time between base and start of network, B_d = distance (km) between base and start of network, and V = vehicle running costs per km. T_n = travel costs around network = $[N_t \times W] + [N_d \times V]$, given N_t and N_d are the travelling time required and distance around the network, respectively. C_u = total trap service costs for unsprung traps = $U_n \times U_t \times W$, where U_n is the number of unsprung traps and U_t is the time to check an unsprung trap. C_s = total trap service costs for sprung traps = $S_n \times S_t \times W$, where S_n is the number of sprung traps and S_t is the time to check a sprung trap.

This model was used to compare the operational costs of a WSN, both with and without a 5-day service-rebaiting visit. With a WSN, the trapper needed only to visit those traps recorded as sprung, but the exact daily travel and labour costs depended on where those sprung traps were in the network. For this they assumed that visiting any subset of sprung traps within the network incurred 50% of the daily costs of travelling around the whole network. Savings were estimated as the difference between operational costs without a WSN and those under each WSN scenario.

To determine a cost-benefit ratio, Jones et al. (2015) used the current commercial cost for WSN hardware, based on a system in which each trap was fitted with a trigger that signalled that the trap had sprung. Up to four traps could communicate with a single node (they assumed a conservative three traps/node). All nodes then communicated wirelessly with a single base-station, which, in turn, passed on the information to the internet via a satellite link. The costs for trap triggers ($40), nodes (NZ $550, including two rechargeable batteries), and solar-powered base-stations (NZ $2,430) were obtained from an Australasian manufacturer. Maintenance and support was assumed to have an ongoing annual cost of 2.5% of those values, with ongoing costs discounted to net present costs using a discount rate of 5% over 10 years.

The annual operational costs of checking all traps daily for 10 days each month were estimated to be $17,654 for a 150-trap network and $29,907 for a 300-trap network. Using a WSN saved approximately 50% of these costs when traps were visited only when sprung (but all traps were visited and rebaited every 5 days). If long-life bait that lasted 10 days was used, up to 70% of operational costs could be saved (Table 1). Cost savings were greater when more traps were included in the network; doubling the number of traps led to a 10% increase in savings using either 5-day rebaiting or long-life bait. Savings also increased when the rate at which traps were sprung declined. For example, for a 150-trap network using long-life bait, monthly operational cost savings increased 58% at a rate of 2.40 sprung traps/100 trap-nights and 79% with a trap-spring rate of 0.76/100 trap-nights.

Table 1 Summary of estimated operational costs from running two differently-sized networks of live-traps and savings accrued from using a wireless sensor network (WSN) to indicate presence of a sprung trap. Discounted annual savings over a 10-year operational life were compared with discounted network establishment and maintenance costs to estimate a benefit–cost ratio for each scenario. Benefit/cost ratios are relative to daily trap checking. Table taken from Jones et al. (2015)

Scenario	Operational costs ($)	Savings ($)	Savings (%)	Establishment costs ($)	Benefit-cost ratio
Daily checks (150 traps)	17,653			35,830	
WSN 5-day rebaiting (150 traps)	8,652	9,001	51		1.57
WSN no rebaiting (150 traps)	6,405	11,249	64		1.96
Daily checks (300 traps)	29,907			69,430	
WSN 5-day rebaiting (300 traps)	13,165	16,742	56		1.58
WSN no rebaiting (300 traps)	8,985	20,922	70		1.97

4.2.2 Kill-trap systems

Because kill traps are not legally required to be checked daily there are considerably more options for how WSNs can be used to: (1) guide the frequency of checking and (2) identify those traps needing to be checked. In general, checking frequency will be determined primarily by bait replenishment requirements, and the rate at which traps fill. Other possible considerations include who is available for checking all or part of the network. That is, if the network comprises traps that are located across private farmland, farmers might be more prepared to check a few sprung traps when they are occasionally notified of a capture, than they would be to commit to routinely checking all traps on their land.

Another issue that needs to be addressed in order to realise the full benefits of using a WSN is the size of a network of traps that is manageable for one trapper. For example, the *Poutiri Ao O Tane* kill-trap network of 700 traps takes approximately four person-days to check. If a WSN was used to inform the trapper when 20% of traps are sprung and only those traps needed checking (i.e. there needs to be long-life bait), checking those 140 traps would take only 0.8 day (i.e. 4 days × 0.2). Thus, if the maximum trap network size is limited by checking costs (i.e. the budget will only fund four days per month), then using a WSN could potentially enable a network of up to 3,500 traps to be managed with the same level of

funding. This example is more complex than described here because it does not account for the costs of the WSN and the logistics of checking traps that will inevitably have larger distances between. Nevertheless, in some scenarios there will be significant benefits from adopting WSNs for remote monitoring, and those benefits will possibly increase as hardware costs decline and, probably as importantly, adopters of the technology learn how to use it effectively.

For kill-trap networks, there are potentially three options for using a WSN:

- Option 1 requires all traps to be monitored, and when sprung traps are detected those traps may then be checked with or without regard to the overall percentage of traps sprung. (This needs a trap bait with a life longer than the checking time.)
- Option 2 requires all traps to be monitored, and the WSN to identify the percentage of sprung traps. At an agreed trigger level, the trapper checks all the sprung traps, irrespective of when they were sprung. (This requires a trap bait with a life longer than the checking interval.)
- Option 3 requires only a proportion of traps to be monitored (i.e. a random sample of traps are selected for monitoring); when the percentage of those traps that are sprung reaches an agreed trigger level then all traps in the network are checked.

Checking traps when, or soon after, they are sprung (Option 1) would not be cost-effective for contractor-based systems, but it might be so when farmers, lifestyle block owners or community groups check traps at essentially no cost to the control programme. Consequently, a large kill-trap network might comprise a mix of all three options depending on the location and availability and willingness of farmers/community members to engage in checking traps.

Options 2 and 3 are more applicable to networks where there are no or few volunteers to check traps and the network has to be managed by a funded contractor. Option 3 would only be selected over Option 2 if the wireless technology was expensive and funding limited to the extent that only some traps could be monitored. How many traps could be monitored, and more importantly, how many should be monitored is addressed in section 4.2.4.

4.2.3 A kill-trap economic model

A simple spreadsheet deterministic economic model was developed to enable HBRC to assess a range of WSN kill-trap scenarios to determine which ones might have a positive benefit-cost ratio (the Excel model will be supplied separately). The model is based on a scenario that requires the trapper (generally a contractor) to check only traps that have sprung when the overall percentage of sprung traps reaches an agreed trigger level (Option 2, above). The input parameters for the model (Table 2) are based on the kill-trap network established for the *Poutiri Ao O Tane* predator control programme. ‘Years for depreciation’ represents the life-expectancy of the technology, after which it would need replacing. Detailed costs of travel time and vehicle costs are not accounted for separately because this model is based on a contractor running the network, who would include these in the daily contract rate. Costs for hardware maintenance and data transmission have not been included because they are not known with any certainty.

Table 2 Kill-trap economic model input parameters and values, based on the *Poutiri Ao O Tane* predator control programme

Parameter	Example values
Number of traps	700
Cost of trap node ($)	$100
Cost of relay station ($)	$1000
Number of nodes to stations	700
Daily contract rate	$400
Person days to check all traps	4
Months to get to 20% of traps sprung	3
Discount rate	0.06
Years for depreciation	5
Months between rebaiting of all traps	12

The model compares the benefit-cost ratio over a range of parameter values (Table 2). Table 3 shows the modelled costs over ten years for one set of parameters values. Using the parameter values listed in Table 2, but changing the price for sensor nodes, indicates that once the price per unit gets much above $100 the system makes a loss from using a WSN (Figure 1).

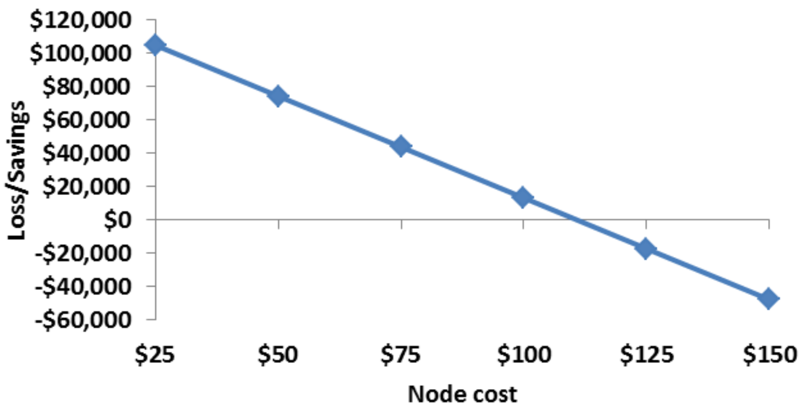

Figure 1 The ten-year cumulative loss/savings from using a WSN with node costs ranging from $25 to $150. Other parameter values as shown in Table 2.

To determine the effect of changing the field-lifespan of the WSN technology, time for the trap network to reach 20% of the traps sprung, and field-lifespan of bait, we used three node prices ($50, $100 and $150) and varied each of the above parameters. Varying field-lifespan from two to ten years (Figure 2) showed that savings increased significantly with increasing time, but also that node price had a significant effect.

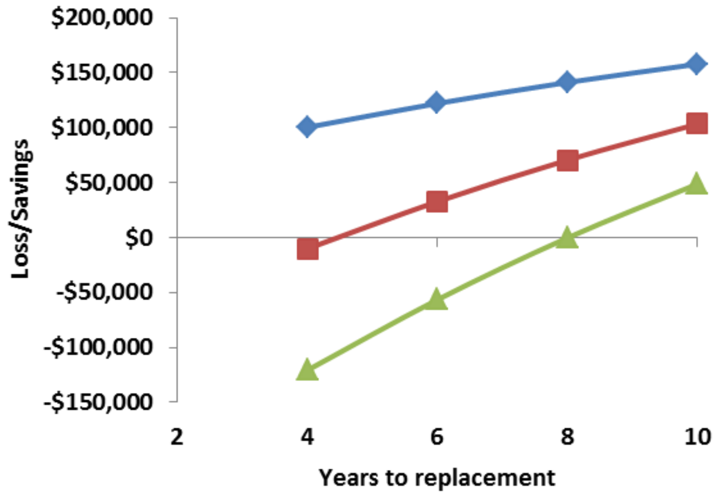

Figure 2 The loss/savings accumulating over twenty years from using a WSN with varying years of depreciation (i.e. years until the WSN needs replacing). Node price is $50 (blue diamonds), $100 (red squares), and $150 (green triangles). Other parameter values as shown in Table 2.

Table 3 Example of costs of running a kill-trap network with and without a WSN. Note this example has used a node cost of $25. Actual parameter values used are listed in Table 2. Likely inflation effects on contractor costs and likely decreases in WSN costs have not been taken into account

	Year										Total
	1	2	3	4	5	6	7	8	9	10	
Full costs of monthly checking traps	20,800	20,800	20,800	20,800	20,800	20,800	20,800	20,800	20,800	20,800	208,000
Discounted costs	20,800	19,623	18,512	17,464	16,476	15,543	14,663	13,833	13,050	12,311	162,275
Wireless costs	18,500	0	0	0	0	18,500	0	0	0	0	37,000
Discounted Wireless Costs	18,500	0	0	0	0	13,824	0	0	0	0	32,324
Cost of checking traps using wireless	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	32,000
Discounted Costs of Checking traps	3,200	3,019	2,848	2,687	2,535	2,391	2,256	2,128	2,008	1,894	24,965
Full trap servicing cost including wireless	21,700	3,019	2,848	2,687	2,535	16,216	2,256	2,128	2,008	1,894	
Savings by using wireless	-900	16,604	15,664	14,777	13,941	-673	12,407	11,705	11,042	10,417	104,986

Once the bait checking time rose above about 5 months, using longer-life baits resulted in only minor increases in savings (Figure 3). If the bait replacement time is shorter than the assumed 3 months it takes the trap network to reach 20% of traps sprung, then using a WSN will result in a loss (Figure 3). When node price was $50 using WSN always produced savings, irrespective of the time between bait replacements.

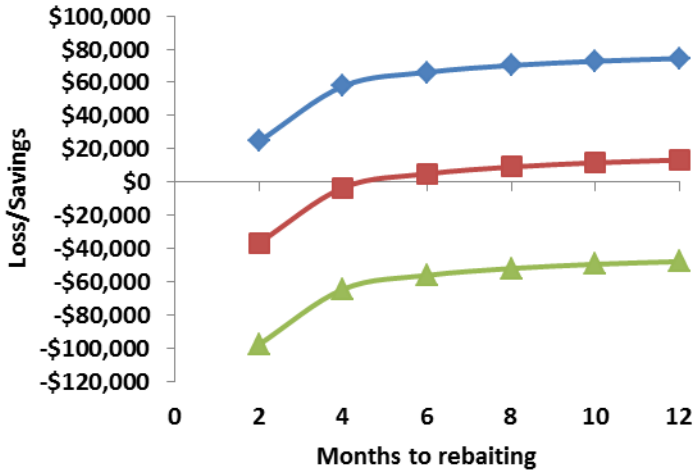

Figure 3 The ten-year cumulative loss/savings from using a WSN with varying time (months) to rebaiting as required by bait field life. Node price is $50 (blue diamonds), $100 (red squares), $150 (green triangles). Other parameter values as shown in Table 2.

Similarly, for each node price, increasing the time for the trap network to reach 20% of traps sprung had little effect on savings once time exceeded approximately four months (Figure 4). However, node price had a significant effect on whether the WSN generated savings or losses.

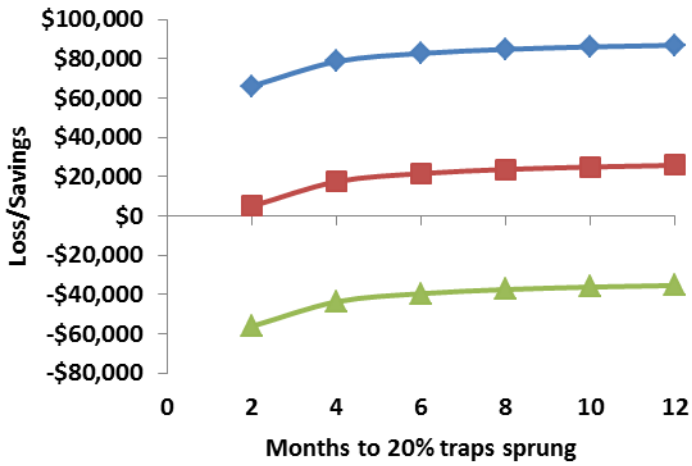

Figure 4 The ten-year cumulative loss/savings from using a WSN with varying time (months) for 20% of traps to be sprung. Node price is $50 (blue diamonds), $100 (red squares) and $150 (green triangles). Other parameter values as shown in Table 2.

Overall, this modelling shows that if nodes cost less than approximately $100/unit, there will be a positive benefit-cost ratio when using WSN. This model assumes that any savings can be realised either by the contractor not billing for the saved time, or most likely, by having a larger trap network to service that will result in a full work day even when only checking a subset of traps.

4.2.4 Monitoring a subset of the trap network

If the cost per node is too high to enable all traps to be monitored, then a representative subset of traps could be monitored to determine when the percentage of traps that have been sprung reaches a trigger level. Since only a subset of traps is monitored, when that percentage is reached, all traps will have to be checked. This design assumes that the subset of traps is selected randomly and accurately represents trap spring rates across the whole network.

The question then is, how many traps need to be monitored to be confident that the trigger level has been reached or exceeded? For the purposes of this report, we have used 20% as the required trigger level, with a stipulation of 95% confidence that the percentage sprung is not less than 15% and not greater than 25%.

A range of sample sizes and confidence intervals were generated (Table 4), using a standard formula for determining the confidence levels of a proportion. About 250 traps would need to be monitored for the confidence levels stipulated. Table 4 shows the implications of fewer traps being monitored because of funding constraints. These figures are not affected by the total number of traps in the network (i.e. no finite sample correction has been applied because we do not know the total number of traps that might be used and the correction does not reduce sample size significantly).

Table 4 Sample sizes and related confidence limits (CL) to reliably detect a true 20% trap-spring rate. Alpha (the likelihood that the true population parameter lies outside the confidence interval) = 0.05; two-tailed. Note CLs are not symmetrical

Sample size (i.e. number of traps monitored)	Mean percentage sprung	Lower CL	Upper CL
50	20	10.03	33.72
100	20	12.67	29.18
200	20	14.69	26.22
250	20	15.22	25.50

5 Conclusions

The paradigm shift some pest managers have recently made from intermittent intensive control to permanent suppression of pest numbers using permanent trap networks, along with the recent development of WSN technology, has enabled potentially significant savings to be delivered by the integration of new management and new technology.

Economic models of both live-trap systems (Jones et al. 2015) and kill-trap systems (this report) show that positive and significant benefit-to-cost ratios can result when WSNs are used to remotely monitor traps.

The extent of the savings from using WSNs will depend on the scale of the networks (the larger the network, the greater the benefit), the availability of long-life bait (the longer the bait life the greater the benefit), and the capture rate (the lower the capture rate and the longer the time for traps to fill, the greater the benefit). Capture rate is a result of both target and non-target captures, so to maximise the benefits of using WSN every effort should be made to minimise non-target captures.

Additional benefits will also accrue if volunteers (farmers/community groups) check sprung traps. WSNs enable a wide range of recipients to receive notification of a trap's status (sprung or still set), and realising the full potential of using WSNs in a wide community of possible trap checkers (responders) will take time.

If long-life baits became available, every trap ideally should be monitored, so a responder would have to check only sprung traps. However, in the event that the price-per-node is prohibitive, the spring-rate of a subset of traps could be monitored to determine when to check the whole trap network. If we accept the network should be checked when 20% of traps are sprung, and we want to be 95% confident that the true percentage lies between 15% and 25%, a subset of approximately 250 traps needs to be monitored. Fewer traps could be monitored if less precision was acceptable. However, if the precision provided by 250 traps was acceptable, then the larger the network this subset of 250 traps represents, the more positive the benefit-to-cost ratio will be.

WSNs will also provide date and time data for each capture, enabling analysis of patterns of capture of both target and non-target species. This might enable trap networks to be further fine-tuned; for example, by using the WSN communication to open traps only during times that maximise target captures and minimise non-target captures.

6 Recommendations

- Field trials continue to test available WSNs so data can be obtained on the technology costs and the savings gained through reductions in trap network servicing costs.
- Systems tested use 160 MHz rather than 2.4 GHz.
- Any roll-out of WSN technology is based on prior economic analyses, at least to obtain some basic understanding of the likely benefit-to-cost ratio.
- Initial tests are based on a subset of traps to monitor only the proportion of traps sprung. Once confidence is gained with the technology, it should be rolled out across a full trap network with a mix of possible trap responders (checkers) involved. This

would enable the use of WSN monitored trap networks to be optimised and the benefit-to-cost ratio maximised.

- The economic models be further developed to capture the full range of possible WSN scenarios influenced by HBRC selected policy and practice.

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