WHAKARATONGA IWI
FIRE EMERGENCY
NEW ZEALAND

EVALUATION OF GRASS CURING ASSESSMENT METHODS FOR APPLICATION IN NEW ZEALAND

Scion

September 2018

Grass goes through a natural process where after flowering/seeding it changes colour as it dies off. This process is known as 'curing.' The degree of curing (%) is the portion of dead vs live matter. Grass fires represent over 50% of wildfires in New Zealand; the greater the curing, the greater the fire risk. Accurate assessments of curing values are critical in the calculation of the Fire Weather Indices and predicting fire behaviour.

The current method for assessing grassland curing in New Zealand is reliant on visual assessments as a general observation of a large area at specified locations. These are often infrequent and don't produce an accurate assessment.

The solution needs to be applied over all New Zealand and frequently.

Fire and Emergency New Zealand Research Report Number 165

ISBN Number 978-1-92-728728-6
ISSN Number 2703-1705

Evaluation of grass curing assessment methods for application in New Zealand

Final report

Veronica Clifford, Grant Pearce, Hugh Wallace, Duncan Steel & Delwyn Moller

Report information sheet

Report title	Evaluation of grass curing assessment methods for application in New Zealand
Authors	Veronica Clifford, Grant Pearce, Hugh Wallace, Duncan Steel & Delwyn Moller
Client	Fire and Emergency New Zealand
SIDNEY output number	60794
Signed off by	Tara Strand
Date	June 2018
Confidentiality requirement	Client to determine
Intellectual property	© New Zealand Forest Research Institute Limited. All rights reserved. Unless permitted by contract or law, no part of this work may be reproduced, stored or copied in any form or by any means without the express permission of the New Zealand Forest Research Institute Limited (trading as Scion).
Disclaimer	The information and opinions provided in the Report have been prepared for the Client and its specified purposes. Accordingly, any person other than the Client uses the information and opinions in this report entirely at its own risk. The Report has been provided in good faith and on the basis that reasonable endeavours have been made to be accurate and not misleading and to exercise reasonable care, skill and judgment in providing such information and opinions. Neither Scion, nor any of its employees, officers, contractors, agents or other persons acting on its behalf or under its control accepts any responsibility or liability in respect of any information or opinions provided in this Report.

Published by: Scion, 49 Sala Street, Private Bag 3020, Rotorua 3046, New Zealand. www.scionresearch.com

Contents page

Executive summary

The Project and client:

This contracted research was funded by Fire and Emergency New Zealand’s Contestable Research Fund. The overall project objective was to evaluate methods for assessing grass curing, and identify the best potential solution(s) for operational application in New Zealand.

Scope:

Undertake a literature review, investigating local and international research on the various methods or technologies for monitoring grassland curing. Summarise the advantages and disadvantages of the various grassland curing assessment methods for operational application in New Zealand. Provide recommendations on the most suitable method(s) for operational application in New Zealand including, where necessary, guidance on needs for further research and/or operational evaluation.

Results:

A literature review summarised the more widely known existing methods and technologies, but also previously considered and more recent/new technologies that have so far received little formal evaluation for application in New Zealand. A total of 17 methods or technologies have been presented to Fire and Emergency New Zealand. These include (but are not limited to) visual, destructive, remote sensing, pasture growth models, soil moisture and fire danger rating relationships, UAVs and hand-held sensors. Based on the available scientific literature, four methods were selected for more in-depth investigation, which are presented here. These are: (1) soil moisture relationships; (2) pasture model relationships; (3) satellite remote sensing techniques; and (4) satellite observations in conjunction with other measurements. A table attached to the end of this Executive Summary (Table ES1) also summarises the key findings for variations of these four methods, in relation to the key questions posed by FENZ.

Soil moisture sensors

The national network of fire weather stations supported by Fire and Emergency New Zealand is being equipped with soil moisture sensors, which warrant investigating this approach. Out of all the methods and technologies, soil moisture sensors are the simplest and cheapest to implement. This method has previously been trialled with some promising results, and the addition of a greater network of soil moisture sensors now makes this approach much more feasible.

In the short term, soil moisture measurements are already collected by 125 Harvest weather stations, and implementing display of this data in FWSYS is easy and already underway. Grass curing values can be estimated based on relationships developed between the degree of curing and directly-measured soil moisture. During the up and coming fire season, these relationships could be improved and validated by examination against actual grass curing values observed at the same weather station sampling sites. One major limiting factor is the accuracy of visual estimates of curing for comparison against the soil moisture measurements. In the longer term, investigating the effects of other factors outlined in this report (e.g. effect of grass species, soil types, and climate regions) will further improve the accuracy of the soil moisture and grassland curing relationship.

Pasture models

There are several available pastoral farm decision support tools (DST) or models to help with animal production and farm management. Out of the 13 that were reviewed for application in New Zealand, three were suitable and showed promise as an operational application for grassland curing. All three will require further validation and fine tuning if chosen for implementation. Out of the three options, two of the pasture models are suitable in terms of the ease of development, and are the next likely cheapest option following soil moisture relationships.

Both the AgResearch (Woodward) and Bayesian (Daily) pasture models are simple models to implement in New Zealand. All the inputs required to get these models up and running are currently available. The advantage of these models is that they are specifically designed to calculate a grass curing value (i.e. proportion of dead grass). However, the AgResearch model was trialled for only one season in New Zealand, and the Australian Daily model has never been trialled for New Zealand conditions or grass types. If adopted, either one of these pasture models will require further field testing in New Zealand for validation and/or fine tuning to New Zealand grassland species before trusting as an operational system. Again, the limiting factor is the accuracy of visual estimates used for comparison against model output.

Remote sensing

Out of the methods and technologies investigated, this is likely the best option for Fire and Emergency New Zealand going forward. Remote sensing would satisfy the requirement for a fully automated system that is objective, regular, and has full spatial coverage across the country. However, this option requires a significant research component for development of a new, improved satellite-based grass curing product. This includes the need to address future-proofing for satellite obsolescence, through transition of curing algorithms from the current MODIS instrument on the Terra & Aqua satellites to alternative replacements (such as the VIIRS instrument on the NPP satellite and upcoming JPSS satellite series).

Following an in-depth investigation, three sources of satellite data have been recommended for trialling a prototype system: the US NOAA JPSS constellation; the Japanese GCOM-C constellation; and the European Sentinel-3 constellation. Each of these can deliver imagery obtained at the required wavelengths, with a suitable frequency (more than once weekly), and with an adequate spatial resolution. Sentinel-3 appears to be the best option, followed by a sister constellation (Sentinel-2), to offer the possibility of higher-resolution imagery.

In the short term, a prototype system based on previously-trialled New Zealand algorithms that make use of the Normalised Difference Vegetative Index (NDVI), and data from the current Terra and Aqua satellites could be developed. It is also suggested that these algorithms be trialled using all three of the satellite sensor platforms recommended as preferred replacements for these soon to be obsolete satellites, to identify the best performing source for future satellite curing assessments. Longer term, and potentially running in parallel, further field research is required to validate and improve the accuracy of grass curing estimates from remote sensing based on the recommendations from the New Zealand-specific post-BFCRC analyses. This would involve research into improving the current New Zealand curing algorithms by: fine tuning to the various grassland types; masking out of other fuel types; refining based on historical curing climatologies; and/or employing alternative indices derived from imagery at other wavelengths (other than the conventional NDVI).

Hybrid model

New Zealand can successfully implement a satellite-based system for monitoring grassland curing over time; however, there have been a few issues identified by Australian and New Zealand researchers with relying solely on this technology. Developing a data fusion approach that combines satellite-derived data with curing estimates from another method would maximise both the accuracy and continuity of grass curing information needed by operational fire managers. A satellite curing algorithm combined with ground-based observations (either visual, or soil moisture or pasture model data) is the best option for New Zealand to implement and will overcome gaps in data caused by persistent cloud cover or satellite instrument error. This is the current strategy in several states of Australia, and there is a move to nationalise this in the near future.

Recommendations

Fire and Emergency New Zealand's aim is to have a fully automated operational system for collating and displaying grassland curing estimates to reduce the uncertainty around current inputs from erratic field observations. In addition, any automated system has the advantage of directly feeding into, as input data, real-time fire spread and smoke prediction tools, currently under development. Previous studies using either soil moisture indicators, the pasture quality model or remote sensing show promise, but much work remains before using these techniques. Any of the identified methods would require validation, running in parallel with an initial prototype operational system, to fine tune the curing product and improve the accuracy further before a fully functional operational system is adopted.

Ground-based observations do not capture spatial variation in curing levels across the whole landscape, whereas satellite observations can provide a curing value for every gridded cell across the country. The major issue is that satellites may not entirely capture changes in curing in the event of consecutive days of cloud cover or satellite errors. Ultimately, satellite observations with gap filling or adjusted by ground observations (soil moisture or visual) provide the most likely means of achieving the aim of a fully automated system with maximum confidence of final curing products.

It is recommended:

- In the interim, either adopt the:
    - Soil moisture method to provide automated tabulated curing data that feeds into the grassland fire danger rating values. This will require validation during the next one to two fire seasons with fire personnel, and fine tuning of the model at the end of the first season if required. This is because the first stages (moisture sensor installations on RAWS) are already underway, and this is the cheapest and least time-consuming option. However, a specific soil moisture model (or models) will need to be developed.

      Or,
    - Remote sensing method to provide automated visual daily rolling maps and tabulated data of curing values to feed into grassland fire danger rating values. In the interim, FENZ can utilise the previously developed prototype maps based on the New Zealand algorithms that makes use of the Normalised Difference Vegetative Index (NDVI), and data from the current Terra and Aqua satellites. However, the map product (either Model B or Map Victoria) will require a few tweaks to address New Zealand specific problems identified from previous research. Again, ground truthing with visual observations from fire personnel are required for validation and further fine tuning, as non-automated curing maps were trialled for only one fire season previously.
- Adopt the approach of the Australian fire agencies and develop a hybrid system combining satellite data with ground observations, as this appears to offer the best potential to meet operational requirements.
    - This could be done by developing a prototype soil moisture model-based system in parallel with implementation of the remote sensing method above. This would allow the soil moisture system, once developed, to be used to fill gaps in the satellite-based map product (e.g. for periods of cloud cover, or satellite errors). This is likely the preferred hybrid approach, due to the satellite remote sensing method (using existing NDVI-based algorithms) currently being the most advanced and closest to implementation ready.
    - Alternatively, however, this could be done by running in parallel to the soil moisture system implementation, the development of and trialling of prototype satellite maps based on a New Zealand specific curing algorithm. The prototype satellite system, once ready for validation, could be compared to the already validated soil moisture sensor network and/or visual observations from local fire personnel, allowing the algorithms to be further improved over time and ultimately perfecting the overall curing product accuracy.
- In the long term, implement an operational hybrid system that combines ground and satellite data to maximise confidence in the final curing map products. A soil moisture-based model using soil moisture measurements would automatically fill in any gaps in the satellite data due to persistent cloud cover or satellite errors, and ultimately be more reliable and straightforward than setting up ongoing field observations from a network of trained ground observers.
    - Algorithms developed for the current MODIS instrument on the Terra and Aqua satellites would need to be transitioned to be replaced by data from the VIIRS instrument (Visible Infrared Imaging Radiometer Suite) on the NPP satellite and upcoming JPSS satellite series.
- The option for visual observations or levy rod measurements to be manual entered should still be present as part of the system, with specified users having the ability to overwrite data if required. These manual entries could also be used to further fine tune the system and allow the algorithms to be further improved over time, ultimately enhancing the overall curing product accuracy.
- A field data collection methodology and associated training package should also be developed and run as part of the validation associated with both the satellite and ground observation (soil moisture) model development, and ongoing ground truthing for the future hybrid operational curing system.

Table ES1. *Summary of key findings for the four grass curing assessment methods, relative to the questions posed by FENZ.*

	Soil moisture measurements	**AgResearch pasture model**	**Daily pasture model**	**GRAZPLAN pasture model**	**Original satellite map using MODIS**	**Replacement satellite maps using VIIRS**	**Hybrid system of satellite & ground**
Ability to directly plug into FWSYS?	Y Easy. Straightforward.	Y Some effort with addition of equations. Straightforward.	Y Some effort with addition of equations. Straightforward.	Unknown. Effort required taking outputs from software into FWSYS.	Y Effort required from satellite data to FWSYS.	Y Effort required from satellite data to FWSYS.	Y Effort required from satellite data to FWSYS
Do we have all the info to get running?	Y	Y	Y	N Need to contact provider (CSIRO).	Y	Y	Y
Can we run the model?	Y	Y	Y	Y At a cost.	Y	Y	Y
Developed in NZ?	Y	Y	N	N	Y	Y	Y / N
How promising is it?	Somewhat promising	Promising	Promising	Somewhat promising	Promising	Promising	Most promising
Is there further work required?	Y Considerable. Requires statistical model(s) built to calculate curing.	Y Considerable. Further work required to improve accuracy.	Y Considerable. Further work required to improve accuracy for NZ grass types.	Y Major. Needs a trial with NZ grass and soil types. See if there are areas for improvement.	Y Some improvements. Further effort required for ground truthing.	Y Considerable. Further effort required for ground truthing.	Y Considerable. Further effort required for ground truthing.
How much effort is required in implementation?	Some. Most work already done, 125 sensors already installed on weather stations. Outputs in Harvest database, soon into FWSYS.	Some. Original model can be incorporated. Better if improved & evaluated over multiple years. May require consultation with AgResearch.	Some. Original model can be incorporated. Better if improved & evaluated over multiple years. May require consultation with AgResearch.	Considerable. Requires evaluation, likely over multiple years. Could be very accurate & adaptable. May require consultation with AgResearch.	Considerable. Effort is required for incorporating into FWSYS. Requires consultation with Scion (FII), NIWA &/or CSIRO, CSST.	Considerable. Effort is required for incorporating into FWSYS. Requires consultation with Scion (FII), NIWA &/or CSIRO, CSST.	Considerable. Effort is required for incorporating into FWSYS. Requires consultation with Scion (FII), NIWA &/or CSIRO, CSST..
How close to being implementable?	25%	30%	30%	40%	60%	50%	<40%
Who has capability?	Scion, NIWA	AgResearch, NIWA	AgResearch, NIWA	AgResearch, Scion, NIWA	NIWA, CSST, CSIRO/BoM, Scion	NIWA, CSST, CSIRO/BoM, Scion	NIWA, CSST, CSIRO/BoM, Scion, AgResearch
Is more science required for gap filling?	Interim, No. But further fine tuning required.	Interim, No. But further fine tuning required.	Interim, No. But further fine tuning required.	Yes, likely. Requires further investigation.	Interim, No. Refinement of compositing required.	Yes. Requires ground truthing, development of compositing.	Yes, depending on ground observation method used.
Costs?	Some	Some	Some	Considerable	Considerable	Considerable	Considerable
Comments	Trialled in NZ. Likely to need to develop specific models for each fire climate zone, based on different grass types/soil types.	Model includes calculation of curing. Trialed in NZ but further developments required.	A more complex model to the AgResearch pasture model. Model designed specifically to calculate curing (%). Has not been trialled in NZ.	The most complex but comprehensive model out of all the pasture models. Trialled in Australia for curing. The pasture model in GrassGo is potentially all we need. Other data required to get the full model running (e.g. grazing specifics).	Not recommended, as MODIS on Terra and Aqua are obsolete soon. Suggestion is VIIRS instruments on other suitable satellites Model designed to calculate curing. Has been trialled in NZ, although improvements recommended.	Model designed specifically to calculate curing (%). Has not yet been trialled in NZ.	Ultimately dependent on ground method satellite observations combined with. Model designed to specifically calculate curing. Methods utilizing field observations already operational in Australia.

Introduction

Brief project background

Grasses undergo a biological process where they change colour as they die off and dry out following flowering/seeding. This is an annual or seasonal cycle, and varies widely from place to place and throughout the season. As grasses die off, this process is known as ‘curing’. The ‘degree of grassland curing’ describes the proportion (%) of dead grass present within the grass fuel complex (Cheney and Sullivan, 2008). The greater the curing value of grasslands, the greater the fire risk in those areas.

Grass fires represent over 50% of wildfires in New Zealand (Doherty et al., 2008) and therefore accurate assessments of curing values to predict fire danger and behaviour are necessary. The main factors that affect the susceptibility of grasslands to wildfire are fuel availability (amount and condition of grasses), fuel dryness (moisture content) and an ignition source (human or natural). The condition of grass fuels, or “grass curing” is a key predictor of grass fire risk, particularly the fire behaviour potential, including ease of ignition, rate of spread and fire intensity (Cheney & Sullivan, 2008).

Grassland curing is an essential input into the New Zealand Fire Danger Rating System (NZFDRS) to determine fire behaviour and danger (Alexander, 2008). The NZFDRS assesses grass fire danger based on information on the Initial Spread Index (ISI) and the degree of grassland curing. This information is then fed into operational fire management decision-support systems such as the Fire Weather System (FWSYS). It is therefore essential that estimates of the degree of curing are accurate for predicting or determining fire danger ratings.

The current operational method to assess the degree of grassland curing (DoC%) in New Zealand is reliant on visual assessments. These assessments are undertaken by fire managers across the country, either as general observations of a large area or at specified locations, often with the use of photographic guides. At times, depending on workloads, these assessments are infrequent and only made at a few locations. This can lead to poor estimates of grassland fire danger and behaviour potential, which subsequently form the basis for operational decision-making by fire managers. Underestimation of curing can have significant consequences for fire authorities should a fire occur. Once grass curing is past 60%, further curing occurs very rapidly during dry periods, and some grasslands may get a second green up with late seasonal rain, while others will continue to die off. Therefore, New Zealand requires at least weekly updates of curing information for the dominant grass types as input into fire danger assessments.

Fire and Emergency New Zealand have an immediate need for a suitable solution. What is required is a cost efficient and reliable method of accurately assessing curing. This system needs to be applied over broad geographic areas, and to provide fire managers with an accurate indication of curing levels within their regions of responsibility.

The aim is to develop an accurate and efficient means to determine degree of curing for day-to-day fire management. With a further objective being to have a fully automated operational system for collating and displaying grassland curing estimates to reduce the uncertainty around current inputs from irregular and highly subjective field observations. Advancements in science and technologies now make it possible to take advantage of new methods to supplement or replace current curing assessments in New Zealand.

Scion was contracted in 2017/18 to investigate techniques for improving the assessment of grassland curing, with emphasis on the applicability of soil moisture relationships, pasture model outputs and remote sensing techniques. This project seeks to identify improvements to the grass curing assessment process that result in a reduction in the subjectivity and improvements to the accuracy of the resulting fire danger assessments used in New Zealand. The outcomes of this project will contribute to improvements in the accuracy and operational use of products for monitoring grassland fire danger. It will enable more accurate estimation of fire potential, including improved identification of conditions for grass fire ignitions and improved accuracy of fire behavior predictions. These, in turn, will result in better fire management and associated outcomes in grass-dominated areas, including reduction in the number and consequences of grass fires through improved fire prevention, protection of life and property, and reduced damage to commercial and environmental assets.

Materials and methods

Research approach

An initial review of literature on historic, existing and new approaches to assess the curing of grasslands was carried out. These findings are included within a separate interim milestone report already provided to Fire and Emergency New Zealand (FENZ) which contains more detailed discussion of each of these wider methods (Clifford et al., 2017). The interim report takes into consideration the technology limitations, practicality, costs and effort required to develop each method into an operational solution, plus the accuracy, frequency, workload and training involved in ongoing application of each of the potential assessment methods, and ease of linking into operational systems such as the Fire Weather System (FWSYS). These findings were summarised in a table (refer to Appendix A) to help identify the best approaches for improving both the current and future performance of grassland curing assessments.

Following the completion of this initial literature review on available methodologies for measuring grassland curing, FENZ confirmed the methods or techniques they wanted to see further investigated. Four options were chosen:

1. Pasture productivity modelling
2. Soil moisture measurements
3. Remote sensing with satellite imagery
4. A combination of above

In particular, FENZ requested reporting on the following:

- How close each of the methods are to being operational/implementable?
- Our ability to implement each of the methods for NZ?
- How far away is that technology from application, i.e. does it need extra steps to complete?
- Describe the steps involved to produce a grass curing output.
- What are the next steps to achieve an implementable system?
- Who has the capability?
- Is there more science needed to fill in the gaps?
- What are the assumptions/limitations?
- What is the best way of combining with remote sensing?

An attempt has been made to answer these questions for each of the four method options (see Table ES1 at the end of the Executive Summary).

This report outlines in more detail the advantages and disadvantages for each of the chosen methods that best suit the New Zealand environment. It also takes into consideration comparisons of technology limitations, practicality, accuracy and costs associated. Finally, it provides recommendations on the most suitable method(s) for operational application in New Zealand including, where necessary, guidance on needs for further research and/or operational evaluation. This will allow FENZ to have an in-depth understanding on what is the best approach currently available.

Results

Soil moisture findings

To date, the use of direct soil moisture data to predict curing has had limited validation to aid operational use. Little research in New Zealand and internationally has advanced on this topic since 2005. A summary of the literature is found in Appendix B.

Scion investigated the relationship between soil moisture content and degree of curing between 1998 and 2002 (NZ Fire Research, 2002b). This work showed that there are promising relationships between the degree of curing and directly measured soil moisture, and also soil moisture indicators within the FWI system (DC and DMC). Relationships between rates of change of curing and soil moisture showed the most promise, rather than direct relationships between the two variable. However, unfortunately, the relationships showed promise for one season, but proved to be poor in the next season (Anderson & Pearce, 2003). Soil moisture is most likely to influence grassland curing over the growing season, during the early part of the fire season, but may be less important when the vegetation is fully cured (dead/dormant). Therefore, it is best to think of soil moisture acting as a trigger for curing. It was recommended that the number of sites be extended to other locations around the country to enable more reliable comparisons to be made. It was also suggested that there are other factors that influence grass curing that warrant further investigation, including different grass types (annual versus perennial) and species, and soil type and its effect on soil moisture. Anderson & Pearce (2003) went as far as suggesting that separate relationships may need to be developed for the different grass type/soil type combinations across the country. The findings from these past studies are further summarised in Appendix B.

The much wider availability of soil moisture data today presents an opportunity for its use in grassland curing estimates and fire danger assessments. In New Zealand, the National Institute of Water and Atmospheric Research (NIWA) has installed soil moisture and soil temperature sensors throughout the country for research purposes and the data is available through the national climate database (Penney, 1997). These sensors measure hourly or daily soil moisture expressed as a percentage by volume (CliFlo, 2018). In addition to the NIWA network, there is a large network of fire weather stations in New Zealand recording hourly soil moisture and temperature. FENZ has installed soil moisture sensors on a total of 125 weather stations that report back to Harvest and eventually to the FWSYS application. With this much greater number of weather stations reporting soil moisture and temperature data, FENZ could now make the best use of this information for estimating grass curing. An enhanced soil moisture observation network could also help in validating the FWI System moisture code values (especially for DC) during the fire season, and to “nudge” calculations where necessary; for example, at the beginning of the fire season when early spring fire danger conditions are elevated due to below normal over-winter rain (Anderson & Pearce, 2003).

Limitations
Soil moisture can vary over short distances and time so that measurements made at one location may not be relevant to neighbouring locations. The variability in soil moisture is due to the distribution and characteristics of precipitation, soil type, vegetation and topography. This spatial variability limits the effectiveness of ground-based point observations of soil moisture. Direct point soil moisture measurements to calculate grass curing values would still be useful for monitoring the fire danger and for providing a “heads up” as to grass fire potential. An alternative and practical way to estimate daily soil moisture over the entire country would be through satellite remote sensing directly of soil moisture or, potentially but less practically, through outputs from a Land Surface Model (LSM).

Review of the literature indicates that international research has progressed since the 2003 analysis, particularly in the area of soil moisture estimation. Remotely sensed data is now the preferred option to estimate curing using either a soil dryness index or relative greenness index (such as NDVI) (BNHCRC 2017; Dharssi et al., 2011, 2012; Dharssi & Kumar, 2015; Ochsner et al., 2013; Ray et al., 2017; Su et al., 2013). Remote sensing overcomes the limited spatial variability direct soil moisture measurements have.

Land Surface Models also produce estimates of soil moisture for a range of depths in the soil profile as one of the many outputs from these complex models. They can simulate changes associated with a range of soil types and, more importantly, vegetation types, based on modelled atmospheric conditions. NIWA uses the Joint UK Land Environment Simulator (JULES), which has been shown to provide good estimates of soil moisture for specific sites in New Zealand (Yang et al., 2014). Use of direct or modelled soil moisture estimates were also shown to improve FWI moisture code accuracy (Yang et al., 2015). However, the practicality of using LSMs for improving grass curing estimates is potentially limited by the current resolution and computing requirements of these models, as well as limited availability of required inputs (soil parameters and, to a lesser extent, meteorological observations) (Yang et al., 2014).

Another option to improve spatial variability could be to adopt similar procedures to those used by NIWA to create their soil moisture maps (see Appendix B for further information). The NIWA maps estimate soil dryness primarily for use by farmers (based on soil water holding capacity and evapotranspiration losses from grass vegetation cover), and this has promise for fire. Once a curing value is calculated from direct soil moisture measurements, this can be combined with NIWAs virtual climate station network and/or a Land Surface Model to produce more accurate spatially interpolated maps for the country.

Direct soil moisture inputs

Sensors currently installed on the FENZ/Harvest weather station network around the country are the Acclima TDT Soil Moisture & Temperature Sensor. Further information on all the various sensor types available are included in Appendix B, along with the advantages and disadvantages of each sensor type. In addition to the FENZ network of TDT soil moisture/temperature sensors, there are several other stations around the country with different sensor types that could be added to the dataset for future validation. However if various sensors are used in a national grassland curing network, each sensor error/sensitivity will have to be accounted for in the algorithm development.

Currently, the reporting frequency for soil moisture (from current RAWS) is hourly on the Harvest website (soon to be in the FWSYS). However, the degree of curing is dependent on several other input variables (see table below). The factors in Table 1 below warrant further investigation.

Table 1. Summary table of potential inputs to improve a basic soil moisture model (Anderson & Pearce 2003)

Factor	Can access data?	Comments
Soil moisture	Y	
Soil temperature	Y	Can affect grass growth (slow or speed up)
Radiation received	N	Require purchase of additional sensor.
Longer term rainfall	Y	
Air temperature patterns	Y	
Soil type zones	N	A map or table like the climate zones for FENZ stations would be needed to identify soil type/characteristics at each location
Climatic zones	Y	
Plant species and type	N	This refers to the growth habits of grass species. Annual grass species will dry out and die off earlier in the dry season than most perennials (such as perennial ryegrass, browntop, Tall fescue, Cocksfoot, kikuyu, clover/pasture mixes, and tussock).
Root depth	N	This will vary for species (annual vs perennial, exotic pasture, to native tussock)

Architecture and workplan

Steps involved for an operational system

Currently, FENZ/Harvest are recording soil moisture and temperature from 125 stations. These measurements are available as raw data values on an hourly basis that can be downloaded. There is a requirement to convert that hourly soil moisture value into a grass curing value (%); a daily value would likely suffice, give that grass curing only changes relatively slowly. The final product(s) are:

- Tabulated soil moisture data, daily for each station.
- A stand-alone grass curing product derived from the soil moisture data, to visualise the change over time (graph and tabular) for each station. This curing value (%) is incorporated into the national and regional summary table.
- A colour coded national map, updated daily, where data is spatially interpolated (similar to NIWA’s soil deficit maps).

Brief descriptions of steps

Short term, collect direct soil moisture measurements into one place (already underway in Harvest, soon FWSYS), and develop a statistical model (or models, e.g. for different soil or grass types) based on a soil moisture relationship with curing to populate the grass curing value. This value is then populated as an operational prototype in the FWSYS (display in a tabular, graph, and/or map graphic).

Medium/Longer term, further development includes incorporating other factors to improve the prototype soil moisture model(s) and ultimately the grass curing value it produces. The potential also exists here to utilise satellite-derived soil moisture observations, or Land Surface Model moisture estimates, and NIWA's virtual climate station network to produce improved spatially interpolated national soil moisture, and hence, grass curing maps.

Detailed descriptions of steps for the short term and longer term

The proposed steps involved in monitoring soil moisture and developing a relationship with grassland curing are listed in Table 2 and the flow chart in Figure 1 below.

Table 2. Proposed stepwise process from soil moisture data to curing product.

Steps:	Description	Comment
Short term		
1	Direct measurements of soil moisture and temperature are recorded on an hourly basis from 125 weather stations scattered throughout New Zealand.	Already underway
1a	Validate the soil moisture readings from the weather stations with physical soil samples. *This step may not be necessary as previous work showed that the data from the weather stations were in fact accurately reflecting soil moisture conditions at the sample sites (NZ Fire Research, 2002b). However, different sensor types may perform differently.*	Not necessary?
2	Hourly soil moisture data from each of the FENZ/harvest stations are displayed in FWSYS. FWSYS displays: Real time and historic soil moisture products.	Planned
3	Conversion of numerical values recorded on an hourly basis using a statistical soil moisture model to create a daily grass curing % value. More than one model may be required for different grass types, soil types &/or climate regions.	Requires significant effort. Consult Scion & NIWA.
3a	Tabulated daily data for each station, incorporated into the national and regional summary table.	Some effort required by NIWA
3b	Tabulated and graphed daily data of stand-alone grass curing product (to see change over time) for each station.	Some effort required by NIWA
Medium/long term		
3c	Colour coded national maps, updated daily, that can show a time series of soil moisture maps are available (to see change over time; similar to NIWA's soil deficit maps). Would utilise the tabulated data, some spatial interpolation required.	Some effort required by NIWA
4	The grass curing % value is used for other fire danger rating codes and indices in FWSYS (as opposed to the present manual entries).	Some effort required by NIWA to switch
5	Develop a protocol and keep the current option in FWSYS for manual entries if the automated value is not available or representative.	Some effort required by NIWA
6	Validation: Establishing grass fuel sample sites at locations near these weather stations. In addition, there is potential to investigate relationships with other FWI codes (in particular DMC and DC) or compare against satellite-derived soil moisture data. a) Plot a time series of direct soil moisture at each station over several seasons. This shows the soil moisture changing over time. If data available use from different soil depths. b) Plot a time series of grass curing for each station for several seasons (from visual observations in field). c) Plot soil moisture measurements AGAINST actual grass curing values measured from the field. a. Shows the rate of change of the degree of curing over time d) Plot soil moisture measurements AGAINST FWI values over time. a. Determine if there is a correlation between grass curing and soil moisture, or DMC or DC. e) If data exists, plot a time series of grass curing measured from satellites. a. Compare with direct soil moisture measurements.	Requires significant effort
6a	Investigate: particularly the effects of soil type, climatic zones, plant species and weather factors on soil moisture trends.	Requires significant effort (and data for different factors)

	Create a summary spreadsheet that lists: Station location, Years of data, Grass type, Soil type/zone, Climate zone.	
6b	Investigate: the potential for the development of other codes/indices similar to the Grassland Curing Index (GCI) and Soil Dryness Index (SDI) as used in Australia.	Requires effort., consult Scion
6c	Investigate: the potential for further enhancements to the soil moisture model(s) via more complex models, e.g. Land Surface Models utilising NIWA's virtual climate network. Volumetric soil moisture, Saturation point, wilting point, Vegetation cover.	Requires effort., consult NIWA

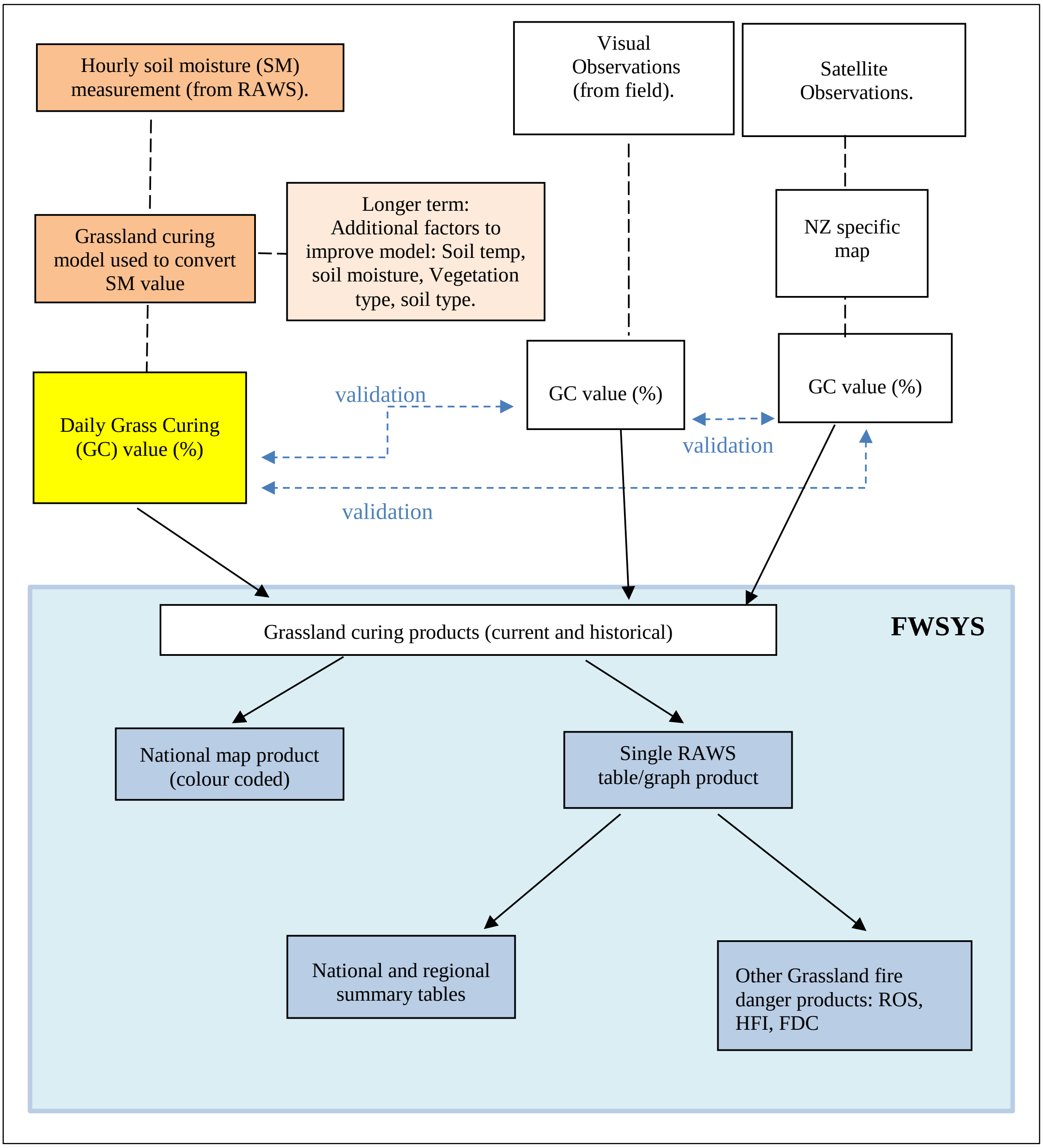


Figure 1. Flow chart illustrating the process from field soil observations to implementation.

Advantages
Using direct soil moisture measurements will provide objective curing estimates, where they are easily displayed into the FWSYS. FENZ can take advantage of this as they have already equipped soil moisture and soil temperature sensors to a large proportion (125 stations) of the RAWS network across the country.

Disadvantages
The biggest issue is deriving a grass curing value with this method. This method has been trialled over a season or two from only a few locations, and with limited success. Multiple models may also be required to account for differences in grass species, soil types, &/or climatic regions. This technique will therefore require considerable further investigation, testing and data analysis before developing a reliable means of assessing the degree of curing from soil moisture data.

Another disadvantage is that direct measurements from a local RAWS location may be spatially unrepresentative of curing across the wider landscape. Utilising NIWA's Virtual Climate Station Network (VCSN) or Land Surface Models could enhance estimates from simplistic soil moisture model relationships. National maps with full spatial coverage across the country could be created from VCSN-derived weather on 5km grids, for example, as opposed to 125 points. Several specific issues are raised from the literature review that a user must be aware of when using soil probes; these are listed in Table 3.

Table 3. Issues or limitations that could affect the measurement of soil moisture and subsequently the calculation of grass curing (Edaphic Scientific, 2018).

Issue	Comments
Installation issues:	The scenario where the sensor is not completely in contact with the soil. a. Most sensors measure the average soil moisture over the entire sensor surface. Having a small portion of a few millimetres not in contact with the soil can lead to drier than expected values. Unexpected air pockets deeper in the soil profile (a dislodged stone), are difficult to counter. b. Solution: always ensure that your sensors and in complete contact with the soil you are measuring.
Calibration issues:	Factory calibration and soil type and precision. a) The factory calibrated value in a sensor or meter will not match the soil you want to measure. b) Ensure sensor is calibrated for each soil type you are measuring. c) The literature also recommends that you conduct soil specific calibrations for accuracy. This is because not all soils have identical electrical properties (due to variations in soil bulk density, mineralogy, texture and salinity, the generic mineral calibration). The electrical characteristics of soil can be sensitive to soil temperature changes (Czarnomski et al., 2005). d) TDR sensors like the ones used by FENZ can be used without calibration, but it reduces the accuracy (Sample et al., 2016).
Soil Texture:	The accuracy of soil moisture sensors is impacted by soil texture. Some sensors that work well in sandy soils with low Available Water Holding Capacity (AWHC) may not perform well in silt loam soil that has high AWHC (Rudnick et al., 2016, Sample et al., 2016).
Measurement output:	Soil moisture sensors have different output values of measurement. The output value can dramatically change your interpretation of soil moisture values. a. This may include: volumetric soil water content (VWC), soil relative water content (RWC), plant available water (PAW), dielectric permittivity, or raw values such as millivolt value (RAW). b. Most sensors are set to a default mode of VWC, but may be set to something else for cheaper models. c. Double check the measurement values of the output. Do not assume your sensors are set the same.
Temperature:	Errors in soil moisture measurements can occur with daily fluctuations in temperature. a. This is spotted with continuously recorded data. b. If the soil shows an increase during the day (and there has been no rainfall or irrigation), and there is a correlation with soil or air temperature, then your soil moisture readings are co-varying with temperature.

	c. This is problematic with cheaper sensors. Solution: double check the data by correlating soil moisture with temperature; if there is a change, then can use complex multivariate statistical models to correct this.
Salinity:	Soil electrical conductivity (EC) can also have an impact on the accuracy and performance of soil sensors. Similar to temperature effects, EC has an effect on how sensors measure the dielectric permittivity of the soil. a. Check the manufactures range of tolerance for EC measurements. b. For example, portable meters are accurate in soils up to 2 mS/cm. This covers the vast majority of plant species tolerance to saline soils. This tolerance is sufficient for agriculture, etc.
Soil sensor depth representative of root depth:	International best practise for installing probes is at 10cm. This represents the surface layer of soil, whereas root zone soil moisture is considered to be in the upper 200cm of soil (Arnold, 2015). Therefore, 10cm may not be the best representative depth for the root zone. a. Further research is required to investigate the best depth for sensors and root depths for various species.
Thatch:	The presence of previous year's dead material in the litter layers can result in underestimating curing (Anderson & Pearce 2003). a. Where dense amounts of compact dead grass litter (thatch) can accumulate in amongst the grass. b. Without a thorough inspection (prising the grass apart), it could be easy to underestimate the amount of dead material. These build ups of dead material may not be reflected in curing estimates made from soil moisture alone.

Pasture growth model findings

There are a number of pastoral farm decision support tools (DST) or models to help with animal production and farm management. Bryant and Snow (2010) reviewed several in the past for pastoral farm management in New Zealand. These include: APSIM, EcoMod, FASSET, GRAZPLAN, GPFARM, Hurley Pasture Model, IFSM, LINCFARM, and WFM.

The advantages of using a pasture model are that it provides objective curing estimates that are made automatically without the need for regular user input. They can be implemented on a medium spatial scale, at weather station locations, but account for wider local climate effects. The disadvantages, however, are that these models are more complex, compared to a simple direct soil moisture measurement (which could also become more complex if you take other factors into account), due to typically being developed specific grass species and/or soil types. A pasture model would require further validation and/or development, and also occasional validation (ground truthing) by fire managers once implemented. We have investigated a number of farm decision supports tools (from New Zealand and Australia) for suitability in predicting grassland curing. These models are listed in Table 4, with summarised descriptions on the following pages and further in-depth information in Appendix C.

Specific models available

Table 4. List of potential pasture productivity models from a literature search on their suitability.

Name	Comment
AgResearch (Woodward)	Suitable. Can be developed quickly and implemented.
Bayesian Model (Daily)	Suitable. Can be developed quickly and implemented. Requires further field testing in NZ as was developed using glasshouse experiments.
GRAZPLAN	Suitable. Appears to function well as a grass curing model in Australia. Possible to develop quickly and article suggests it may also be modified to automatically output curing.
GrassGro™	Potentially useable, this model forms part of GRAZPLAN and uses a pasture model.
Sustainable Grazing Systems (SGS) Pasture Model	Does not inspire confidence
McCall model	Not suitable
Pasture Growth Simulation Using Smalltalk (PGSUS)	Not suitable
Hurley Pasture model	Not suitable
The BASic GRAssland model, based on LINGRA (BASGRA) model	Not suitable, has a useful feature with frost/snow curing.
The Agricultural Production System Simulator (APSIM)	Potentially useable, does not inspire confidence
Pasturebase	Not suitable
The Simulateur mulTIdiscipli-naire pour les Cultures Standard (STICS)	Not suitable
The Canadian Timothy model (CATIMO)	Not suitable

AgResearch (Woodward) model

A Pasture Quality (PQ) model developed to support grazing management decisions on New Zealand farms (Woodward, 1998). It is a simple model designed to capture the biological processes in grazed pasture and has undergone improvements following validation (Woodward, 2001). Scion's Greg Baxter joined forces with AgResearch's Simon Woodward in 1999 and trialled the PQ model for predicting curing in New Zealand (Baxter & Woodward, 1999). The model can calculate the amount of grass, cover and dead matter present in pastures, as well as the amount of live (green) material (Woodward et al., 1998; Woodward, 2001). It seems somewhat promising and suitable to the New Zealand environment, but requires further work (Baxter et al., 1999; Anderson et al., 2003) to inspire confidence for operational application.

The advantages are:

- This model was developed in New Zealand for monitoring curing in mixed ryegrass-clover pastures. Therefore, FENZ would use an already existing system rather than trying to modify a model built for a different purpose.
- New Zealand has all the inputs that are required to get the AgResearch model up and running
  - The inputs include the 1998 Woodward PQ model which requires three daily weather parameters: mean daily temperature, daily rainfall (mm) and daily radiation receipt (MJ/sq m) (and/or number of sunshine hours per day).

Disadvantages

- Research is required to demonstrate proven relationships with grassland curing as it was only tested for one season and at a limited number of sites.
- This model requires more testing as it was not validated for other grassland types.

If chosen for operational implementation, the model requires time for further improvements and examining the relationships the following factors have on grass curing**.** The examination is run over a season (or several) and, during that time, checked with visual observations of curing or from the levy rod technique (Anderson et al., 2005) to see if it's producing reasonable values. This includes:

- Establishing the dominant grass fuel types in each weather station zone and validating the model. Currently, the model is based on ryegrass-clover, which might not be applicable to other grassland dominated areas across the country.
- Establishing timing of seed head development for locations around the country and individual dominant grassland species. The present date default of 30 September is too simple and inflexible. Weather varies from one season to the next, and when combined with soil type differences, will affect the onset of senescence. Work is required to determine the dates for first stem elongation (the initiation of the curing cycle) for different species.
- Modification of the model to adequately reflect the growth and death processes in other grassland fuels of species differing from the initial Woodward PQ model (ryegrass-clover).
- Requiring the water balance process to be tuned to specific soil types and the root zone areas (25mm deep). This will increase the ability of the model to estimate 'die-off' during years of extreme moisture stress.
- Incorporation of a "second growth" (resurgence of growth following a wet period late in the fire season).
- Weather inputs required for the model are different to those currently used in the FWI subsystem component of the NZFDRS and will need re-aligning.

Woodward (2001) outlines in his paper what the pasture model looks like. It requires seven equations to calculate the net daily growth of pasture (Figure 2).

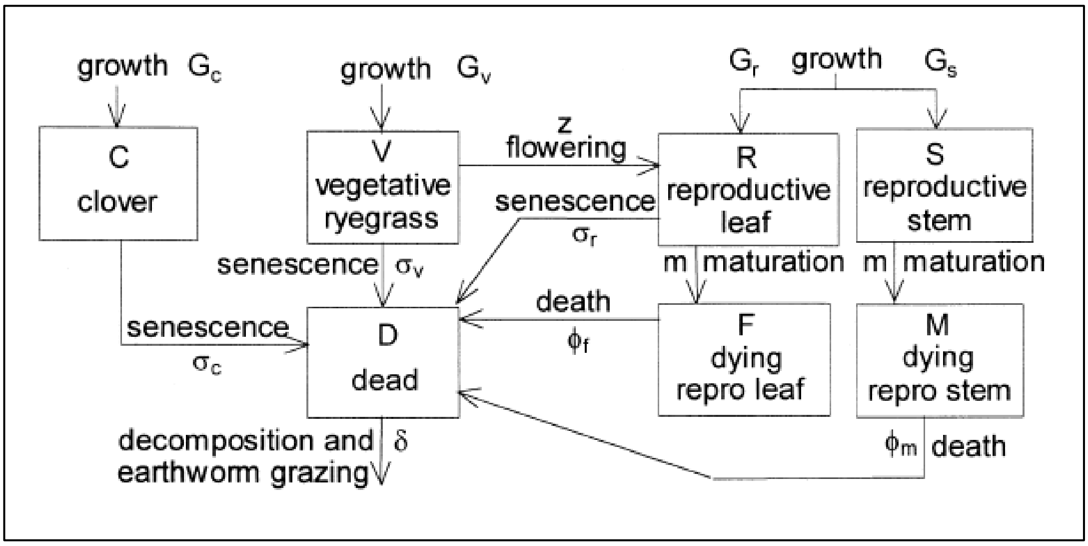


Figure 2. Example of the pasture processes represented in the PQ model. Source: Woodward (2001).

Agricultural models

The simple PQ model was last developed in the early 2000s. The focus in New Zealand was on green matter production for the dairy industry, which is not especially suitable for monitoring grassland curing. The plus side is that they are simple to implement (developed for farmers). The most recent iterations of pasture models are the AgPasture model that forms part of APSIM and Dairy Mod (which again is not very strong on dead matter). These dairy models would need adapting for monitoring grassland curing.

The most widely used models in use in the dairy industry are the:

- DairyNZ model / McCall pasture model (McCall & Bishop-Hurley, 2003);
- The Hurley Pasture model (Johnson & Thornley, 1982; Thornley & Johnson, 2000);
- NZ based PGSUS Pasture Growth Simulation using Smalltalk (Romera et al., 2010).

The models require inputs of daily weather data, including mean, minimum and maximum air temperature, solar radiation, rain and potential evapotranspiration. Data is usually obtained from NIWA’s Virtual Climate Station Network (VCSN).

Other pasture models that were investigated and were unlikely to be suitable or dead ends because they were weak on dead material build up, include:

- The BASGRA model (Höglind et al., 2016)**,** which mainly focused on the winter stress and survival of plants. It is not viable as an independent curing model, but may have a useful feature in modelling the rates of senescence through frosts/snowfall during winter for places around the country that experience cold temperatures during the growing season.
- Pasturebase (Hanrahan et al., 2017),
- APSIM (Holzworth, et al., 2014; Vogeler, et al., 2016),
- STICS and CATIMO (Jégo et al., 2013; Jing et al., 2012).

GRAZPLAN models

GRAZPLAN is a family of tools developed for the grazing industry and farm productivity in Australia (CSIRO, 2007). **GrassGro™**, is a discrete computer package within GRAZPLAN, developed for Microsoft Windows for the sheep and beef industry. GrassGro utilises a pasture growth module and combines with another tool, Grazfeed, to determine pasture and animal production. The GrassGro model within GRAZPLAN is promising and is already in use in Australia to estimate both grass curing, and fuel loading. This GrassGro model represents the phenology, growth, death and decay of annual and perennial pasture species (i.e. Phalaris, White clover, Capeweed) on a daily time step.

GrassGro appears to function well as a grass curing model for Australia. The model was developed originally for Australian conditions, but also run in Canada. This indicates that it is flexible for application in New Zealand and will adapt well to our climate and grass fuel types. If interested further, the pasture growth and soil moisture sub-models are outlined in Moore and Freer (1997).

The outputs are displayed in tabular or graphical (bar or lines) forms, and therefore may not require much effort for integration into the FWSYS. The data outputs allow the user to easily visualise and monitor changes over a full year. The user can also run comparisons of simulations for pasture production to see how an average year compares to a forecast extreme dry year.

The GrassGro model will still require evaluation for operation in the New Zealand environment. To understand whether the model needs improvement or not, trialling of a prototype system over a few seasons is essential. Further work is also required into integrating this software/user interface and its outputs into the FWSYS system.

The issues around these decision support tools is the required expenditure of effort in learning how to use them. Costs include purchasing the software, and required maintenance of the technical content. The interface may be re-built every 5-10 years (from Windows to another environment). It is unclear whether access to the underlying model equations could be purchased separately. GrassGro and similar models require access to a large weather database for inputs into the model, and filling the gaps in weather data when missing is vital (Donnelly & Moore, 1997).

Advantages of the GRAZPLAN model

- FENZ already collects the input data required to run the model.
- Includes the effects of grazing.
- GrassGro can estimate fuel build up, curing and fire risk in annuals and perennials.
- Outputs include: (1) Load: total live/dead biomass as dry weight; and (2) Curing: dead standing and litter vs total biomass as a percentage (%).

Disadvantages

- Developed specifically for Australian grasslands. Further validation is required before operational implementation.
- Very likely to require the addition of New Zealand grass fuel types.
- Currently do not have all the information to get it up and running, and would need to request this from the provider.
- Considerable development period to either prove, or adapt or develop New Zealand fuel models.
- Would need to have an understanding of the program assumptions, terms and logic.
- It requires training to implement and run.
- A minimum of three years (over a few curing seasons) is needed for observation to model evaluation.

Daily models

Daily's research focussed on comparing three pasture models (APSIM, GrassGro™, SGS Pasture Model) and how they performed for several different grass types (introduced pasture and cereal grasses) in Australia. These plant growth models are not focused on curing specifically, and ignore differences between annuals and perennials (animals don't eat last year's vegetation so assumes this does not matter; conversely for fire risk, last year's fuels do matter). None of these models produce curing outputs directly, but this is more of a programming issue. All performed relatively well in relation to the Levy rod grass curing assessment method. But suitability is best for:

- GrassGro – best modelled improved pastures, and grazing effects.
- APSIM – cereals.
- SGS - can best manage native grasses (although only some species).

These models were not able to regularly produce reliable curing estimates compared to the field assessments of curing, in part because the current state of knowledge on the senescence stage of leaf development was not easy to incorporate into the models.

Daily (2012) developed a basic "leaf curing model" and then a **Bayesian model** that included the full range of leaf turnover characteristics calculated from glasshouse grown plants. Daily was able to validate the later model with that in the field (Levy rod), and suggested that this would provide a higher level of accuracy of grass curing prediction than the three pasture growth models that were investigated. Refer to Daily (2012) for what the models look like.

Advantages

- FENZ already collects the input data required to run the best of the Daily models, the basic leaf curing and Bayesian models.
- These are grass curing specific models so there is no need to add a grass curing calculation.
- These performed better compared to the three decision support tools (APSIM, GrassGro™, SGS Pasture Model) in Australia.
- The leaf curing model works in principle, but this is only based on glasshouse experiments not *in-situ* experiments
- The Bayesian model was superior to the basic leaf curing model and could be used to improve the GrassGro model.

Disadvantages

- Further research and validation is required as it was originally developed in Australia, especially for our New Zealand grass species/types.
- A minimum of three years, over a few curing seasons of observations to model evaluation is required.
- Struggles to deal with "recovery"/second green-up events after beginning senescence.

Architecture and workplan

Both the AgResearch (Woodward) and Daily Bayesian models are easy to implement in New Zealand compared to GRAZPLAN. The advantages are that the FENZ fire weather station network already has all the inputs required to get the models up and running. These models were also designed specifically to calculate a grass curing value. However, the AgResearch model was trialled for only one season in New Zealand in ryegrass/cover pasture, and the Daily model has not been trialled in New Zealand conditions. If adopted, the pasture model will require further field testing in New Zealand for validation and/or adjusting to local grassland fuel types before it can be trusted as an operational system. Refer to Figure 3 and Table 5 for suggested steps for implementing this method.

Basic steps:
In the short term, convert required input data on a daily basis into a grass curing value (%). This value is then populated as an operational prototype in the FWSYS (display in a tabular, graph, and/or map graphic). The curing value is then compared with that observed from the identified end-user test group. At the end of the season, investigate whether there is a strong correlation between the populated curing values and those observed in the field. If so, move on to the implementation phase; if not, further fine tuning of the pasture model and another few seasons of field testing are required.

Medium/Longer term, further development including other factors, such as different species and/or soil types, may be required to improve the current prototype and ease of implementation into the FWSYS, if the model is suitable. Then the development of a colour coded national map, also updated daily, would be beneficial to visually see the changes of curing or differences across the country. Investigate whether the calculated curing data from the model can be spatially interpolated using NIWA's virtual climate station network or a Land Surface Modelling approach.

Table 5. Proposed stepwise process from a pasture model to curing product.

Steps:	Description	Comment
Prototype system developed		
1	Choose and develop a prototype pasture model system based on the literature. Ideally develop a system so that it can fit into the FWSYS and curing values are automatically populated.	Some effort required by FENZ & NIWA
2	Select fire end-users to help with the validation process and those who are willing to monitor the calculated curing values against field observations over several seasons (one season is realistically not enough; a minimum of three, and five is best).	Some effort required by FENZ
3	Collect required inputs based on the requirements of the chosen pasture model. Data should be collected daily at each station, for at least one field season, then perhaps weekly in subsequent seasons.	Little/no effort required
4a	Conversion of inputs into a percentage value using the pasture model. Either build into the FWSYS to automatically calculate values or manually enter these into the system or provide as an Excel spread sheet to capture data.	Little/no effort required
4b	An initial prototype product is displayed as either: • Tabulated data (numerical values on a daily basis) for each station, incorporated into the national and regional summary table. • A stand-alone grass curing product to see the trend change over time (graph and tabular) for each station.	Some effort required by FENZ
Validation process		
5	During the first field season, chosen fire end-users need to monitor curing in their patch and provide their estimates or compare to the estimated values and offer advice if the system is producing accurate results. The minimum number of field seasons should be three, five field seasons would be better. The limiting factor is the accuracy of visual estimates to be used for comparison, so end-users will need to be specifically trained.	Requires effort and consultation
6a	To date, no further validation of pasture models to predict curing was carried out in NZ, but has been in Australia. Validation is needed before operational implementation to see if the	Some effort required by either Scion or NIWA

	pasture model addresses grass curing accurately; and an end-user test user group would be required to confirm the model outputs. At the end of the season, identify if there is a statistically strong relationship between the pasture model and grass curing. If not, further investigation and development would be required.	
6b	Further investigation and development in this space may be required if the model needs fine tuning before it becomes a fully trusted operational system. AgResearch are the leading CRI in the pasture modelling space and can provide expert advice. This is to improve the accuracy and ensure confidence of the system as an operation application. In particular: the water balance model, the onset of reproductive development and fine-tuned to other grassland types.	Requires effort. Consult Scion, AgResearch &/or NIWA.
7	Run a fine-tuned model for a second season. Further field testing for validation is required. If end-users confirm that the model calculates accurate grass curing values, this then can be implemented as an operational system.	Requires effort and consultation
Implementation		
8	Implement this improved curing product in the existing national FWSYS.	Little/no effort required by NIWA
9	Investigate and develop colour coded national maps of grassland curing, also updated daily to visually see the changes of curing or differences across the country. Investigate whether the calculated curing data from the model can be spatially interpolated, similar to NIWA's soil deficit maps using NIWA's virtual climate station network or a Land Surface Modelling approach.	Some effort required by NIWA
10	Display curing data as time series of curing maps in the FWSYS.	

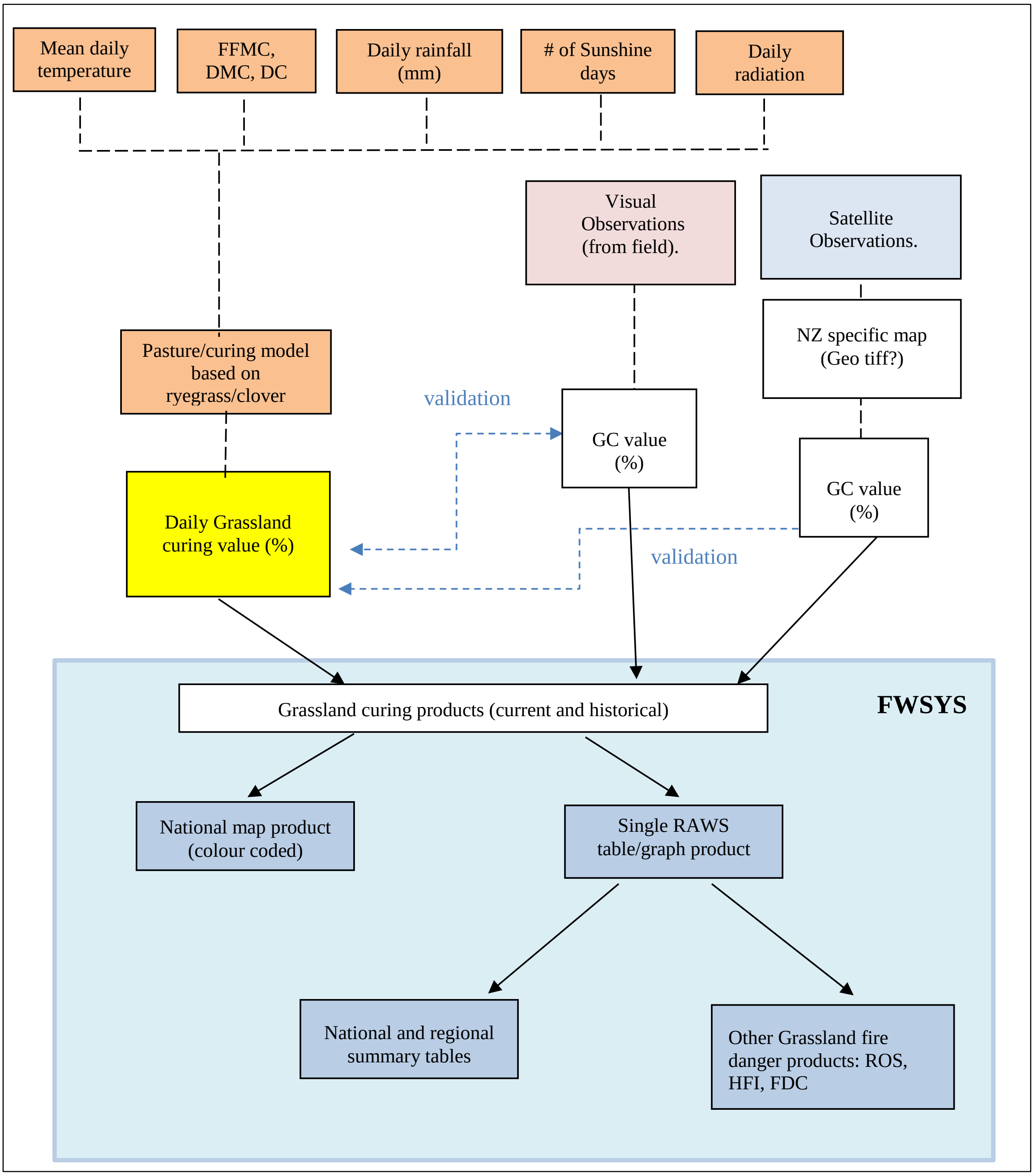


Figure 3. Proposed stepwise process using the AgResearch (Woodward) model for delivering a grass curing value (other pasture models would follow a similar path, with potentially different input values).

Remote sensing findings

In the last two decades, both Australia and New Zealand investigated various techniques for assessing grassland curing. The legacy project undertaken by the Bushfire CRC hosts a wealth of research investigating the relationship between satellite imagery and curing percentages for use in grassland fire danger monitoring (summarised in Clifford et al., 2017). Newnham et al. (2010) found that satellite imagery showed greater accuracy of measuring grassland curing across an entire landscape when compared to ground-based observations. Recent advancements in the science now make it possible to take advantage of satellite remote sensing technologies, and the correlations indicate encouraging results. For further background reading on remotely sensed grass curing, refer to Appendix D.

A prototype NZ system

Newnham et al. (2015) identified the two best performing models for New Zealand using MODIS data collected by the Terra and Aqua satellites. Refer to Appendix D for further background on these models. These models are the Bushfire CRC Map B model and the newer Map Victoria model, the descriptions of which models are contained in Newnham et al. (2015). One version is a simple linear model, the second is a weighted model. Newnham (2015) suggests that the weighted model had little effect, so there was no additional benefit in using it. The issue is that while the linear model fits better, it still tends to underestimate curing at higher levels.

Before an operational application for New Zealand is adopted, the satellite map products (Bushfire CRC model B, and Map Victoria model) require further tweaking to address general and New Zealand-specific problems identified from research undertaken since the investigations in 2015 (Newnham et al. 2015; Wright et al., 2016), including:

- Addressing processing issues to ensure maps are created in a timely fashion and are evaluated against ground-based measurements in real time.
- Satellites can under-estimate curing if woody vegetation and secondary grass growth is present, and over-estimate curing in regions with water-bodies, urban areas, sand dunes and landscapes covered by yellow flowers. Pixels can be masked out where land use and vegetation classes are not grasslands to remove these effects.
- Coarse resolution satellite data may not cover the local variability, so using higher resolution bands would better match the finer resolution ground cover.
- The need for gap filling of curing estimates (e.g. due to persistent cloud) is likely a major issue for a New Zealand operational grassland curing system, and some form of image compositing or model data fusion is necessary to overcome this.
- Curing may not be captured entirely by a satellite in the event of consecutive days of cloud cover. The development and evaluation of composite satellite images from several days could mitigate missing data. Determining the best length for this compositing period is also necessary.
- Future proofing for obsolete satellites, by transitioning algorithms developed for the current MODIS instrument on the Terra and Aqua satellites to be replaced by the VIIRS instrument (Visible Infrared Imaging Radiometer Suite) on the NPP satellite and upcoming JPSS satellite series.
- Investigating whether a detailed area map for soil exposure can counter the errors created by using NDVI (Martin et al., 2015).
- It is essential that New Zealand designs a sampling program and training material for ongoing ground-based sampling to calibrate and validate satellite-based curing estimates.

Optimal temporal and spatial resolution for grass curing

Today, the majority of Australia uses 500m MapVictoria data, where the Bureau has a direct feed of MOD09A1 satellite data. The Bureau produce a modified compositing algorithm resulting in a rolling daily product that consists of the best quality observation data of the last 8 days including the current day. This product is accompanied with a “Satellite Data Age” product, informing how old each observation is in number of days. Using the MapVictoria equation, the Bureau provides a daily satellite map of curing.

In Victoria, the Country Fire Authority (CFA) produces a Victorian Improved Satellite Curing Algorithm (VISCA) map once a week (combining the most recent MapVictoria map with field observations). When curing is climbing rapidly, maps are produced twice a week upon request (from the chief officer). For inputs into the grass fire danger index, VISCA curing maps are grouped to 3km (for VIC and TAS) and to 6km (for SA, QLD, ACT and NSW). For inputs in to the fire behaviour model, Phoenix, VISCA maps are also produced at 500m resolution.

In the previous New Zealand pilot studies (Clifford, 2011), with help from the Australian Bureau of Meteorology (the Bureau) and CSIRO, fortnightly curing maps were trialled. However, this was not optimal as we were limited to the standard NASA processing times (12-14 days) and compositing period (8 days). The latter was somewhat okay as a means of combatting cloud cover, where there was a need to take the best portions from several images to get a complete national map with clear-sky conditions. But because curing can happen rapidly over the drier parts of the season, especially after 60%, it would be better to get at least weekly updates of curing maps, or better, rolling daily composites, as are currently being employed in Australia. However, the optimum compositing period for New Zealand is still to be determined (Australia is currently still using 8-day composites).

The original Landsat derived curing imagery had 1 km pixel resolution, and the previous MODIS imagery 500m resolution. While this may be suitable for extensive grassland areas, such as in Australia, even the latter is probably too large for New Zealand's more fragmented, high intensity agricultural areas, where grass curing may vary significantly from paddock to paddock depending on grazing management. Pixels may also include other neighbouring vegetation, such as horticultural crops or forestry woodlots, where the green canopy can skew curing towards lower values than present in the adjacent grasslands. For this reason, Newnham et al. (2010) recommended refining the MODIS imagery down to a 250m resolution, which is possible from the native 500m resolution. Masking out of non-grassland vegetation types may also help improve this problem.

Specific satellites and sensors suitable for NZ today

Since the previous work undertaken by Newnham et al. (2015), another search of the literature (by experts from the NZ Centre for Space Science Technology (CSST) as co-authors to this report) considered all possible satellites and sensors which might be of use for a New Zealand algorithm based on the conventional NDVI. This involved a total of 49 presently-orbiting satellites. From those 49, many satellites were dropped (e.g. the commercial satellites have swaths that are too narrow to render useful imagery on an individual basis). A more detailed analysis of the characteristics of the satellites and their associated sensors is included in Appendix D.

A summary table is also presented in Appendix D that pairs down the 49 to sixteen satellites along with an explanation. From this detailed evaluation, the top choices are as follows:

(1) NOAA JPSS constellation:
- Operated by the U.S. National Oceanographic and Atmospheric Administration (NOAA).
- Spatial resolution of VIIRS sensor is 375 metres for the bands necessary for NDVI evaluations.
- Two satellites are currently in orbit providing daily coverage of NZ, this frequency may increase if additional satellites are placed in the constellation (as planned).
- Spectral bands include the visible Red light, and the Near Infra-Red (NIR) wavelengths necessary for NDVI derivation.

(2) GCOM-C1 (plus sister satellites anticipated):
- Operated by the Japanese Space Agency (JAXA).
- Spatial resolution 250 metres for NDVI.
- Revisits every two days (this will reduce if the anticipated sister satellite eventuates)
- Spectral bands include the Red and NIR wavelengths necessary for NDVI derivation.

(3) Sentinel-3 constellation:
- Developed by the European Space Agency (ESA), operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).
- Spatial resolution of the Ocean Land Cover Instrument (OLCI) sensor is 300 metres for all bands; 500 metres for the Sea and Land Surface Temperature Radiometer (SLSTR) sensor.
- Two satellites (Sentinel-3A and -3B) provide daily coverage between the pair.
- Spectral bands include the Red and NIR wavelengths necessary for NDVI derivation.

(4) Sentinel-2 constellation:
- Two satellites operated by the European Space Agency (ESA)
- Spatial resolution 10 metres for NDVI, 10 or 20 metres in other spectral bands of interest
- Revisits every five days between the pair (though slightly more often at NZ's latitude); current temporal coverage is therefore too infrequent to deliver weekly useful imagery
- Spectral bands include the Red and NIR wavelengths necessary for NDVI derivation.

Note: the above options also capture other spectral bands across the visible range including at the Red Edge, in the NIR, and in the SWIR, which are of relevance for other useful vegetative cover studies. Some of these sensor offers polarisation measurements in the Red and NIR bands used for NDVI evaluations, and these may be invaluable in terms of investigating how the scattering of sunlight by grass is affected by the solar illumination angle (see the Appendix D for further details).

Architecture and workplan

Table 6 and Figure 4 show a system architecture for the satellite-based grass curing workflow, with data acquisition, image processing, and production of output Grass Curing Index (GCI) maps in an automated fashion using the satellite products identified above. Initially this would include basic processing (cloud cover masking, calculation of NDVI and subsequent production of GCI product layers) for delivery using heritage algorithms. It would be possible to develop and assess, in parallel, enhanced and customized GCI algorithms (e.g. for region and grass type), and then incorporate them into the operational system after validation.

A multi-stage programme concept is proposed in Table *6*, based on steps and work effort estimates provided by CSST remote sensing experts. The initial project comprises establishment of an operational system (phase A in the table); this is then enhanced via phases (B) and (C).

It is strongly recommended that better-performing NDVI-based GCI algorithms for New Zealand conditions be developed through an experimental programme employing historical (and ongoing) data (Newnham et al., 2015). This would include examinations of how well variant GCI algorithms function when applied to different types of New Zealand grassland. Any improvements can be directly integrated into the operational system developed under Phase (A) in table below.

It is also recommended to make use of imagery at other wavelengths, for example in the shortwave infrared (SWIR). This is outlined more in Appendix D, where some recently-launched satellite sensors are returning imagery for visible wavelengths where chlorophyll absorption dominates, providing another channel through which improved GCI algorithms are potentially feasible.

Table 6. Proposed itemising of tasks that are required, with estimated work effort (not schedule) and allocation (RSE = Remote Sensing Engineer, SE = Software Engineer).

Task	Description	Approx. Effort
(A) Satellite-based Automated NZ specific GCI Monitoring System		
1	Identification, classification and demarcation of regions of interest. In concert with Fire and Emergency New Zealand (FENZ).	2 weeks effort (RSE)
2	Automated retrieval of selected multispectral products from data portals.	2 weeks (SE)
3	Assessment of orbits and viewing angles/limitations due to illumination angles and shadowing – develop masking criteria including cloud masking from satellite providers.	3 weeks (RSE)
4	Code existing Bushfire CRC/Scion algorithms for immediate capability using recommended satellite data sources (derive NDVI followed by GCI).	4 weeks (SE)
5	Data fusion (spatial mosaicking and temporal filtering) of various passes to provide layers within a GIS application (for overlaying with other georeferenced data files), or in map formats suitable for display on tablets wielded by observers obtaining in situ data (i.e. visual assessments of grass curing, soil moisture measurements).	4 weeks (SE) and 1 week (RSE)
6	GCI map formatting and automated delivery to Scion/FENZ *Ensure that the data will be processed in a way that overcomes the current limitations in satellite data (such as projection and resampling) used in Australian curing map production. Implementation of routine production of curing maps may require consultation with Scion, CSST and/or NIWA to understand the FWSYS data processing systems.*	2 weeks (SE)

(B) Grass Curing Index algorithm		
1	*Develop curing map algorithm and methods optimised for the highly fragmented NZ landscapes and for detecting rapidly changing phenomena (such as rapidly changing curing state).* Historical evaluation of data to calibrate the GCI for different grass types across NZ. Whilst research directed towards these ends was conducted elsewhere, and published in the scientific literature, the special conditions of NZ argue for the development of a GCI tuned to the peculiar conditions here; indeed, distinct GCIs applied to different types of grassland (e.g. indigenous tussock grass in Otago, low-producing pastoral grassland in the South Island, and high-producing exotic grasslands in Southland, on the Canterbury plains, and across much of the North Island). Fifteen years of historical MODIS (GSD 250 metres, daily passes) imagery could be assembled, for comparison with visual curing evaluations, soil moisture data, and records of actual grass fires; MODIS data have been used by the Bushfire CRC and Scion in previous trials aimed at assessing GCIs. This task would enable evaluations of candidate GCI algorithms, both making use of the conventional NDVI alone, and additionally employing other spectral bands.	4 weeks (RSE)
2	Investigation into additional wavelength bands. The literature and 'stretchy science' allude to improved forms of GCI when other wavelength bands (rather than just the Red and NIR contributing to the NDVI) are utilised. Further investigation with an experimental programme employing historical (and ongoing) data as there are now for operational satellites with sensors designed to cover these specific wavelengths.	3 weeks (RSE)
Validation		
1	Designing a sampling program and field staff training material for ongoing ground-based sampling to calibrate and validate satellite-based curing estimates. FENZ and researchers must undertake further validation and calibration to ascertain the accuracy and reliability of the maps and the suitability of the data for integration into their fire danger rating and fire behaviour systems. Researchers, data providers and fire management agencies should continue to work together to refine the recommended methods, where possible based on objective field measurements.	
2	Where a need for further model development is identified, objective field measurements should be collected using either visual or the Levy Rod method developed by the legacy Bushfire CRC project. This applies particularly to regions that have not previously been sampled, and regions where the recommended model is found to perform poorly.	

The advantages of remote sensing:

- Provides objective updates.
- Full spatial coverage across the country.
- Can be automated to ensure regular and timely curing estimates.
- Increased accuracy compared to ground measurements, including both highly-subjective visual observations and other point-location methods.
- Satellite data is freely available.
- Depending on the satellite used, updates can be done frequently and potentially even daily (as opposed to the fortnightly basis of previous trials).

Disadvantages:

- A prototype system requires further development and testing before implementation.
- Existing algorithms require improvement, as well as extension and validation across all the major grasslands types.
- Resolution of the imagery can under or overestimate curing in fragmented landscapes (i.e., MODIS has lower spatial resolution).
- Gaps can occur in data where cloud cover and reflectance from snow causes "noise" in imagery.
- Access to consistent, good quality (high resolution) satellite coverage comes at a cost.
- Requires futureproofing for satellite obsolescence, with updating required to accommodate newer satellite and sensor technology.
- The MODIS instrument previously trialled will be replaced by VIIRS, although an adjusted process is expected to work with VIIRS (VIIRS has similar, but not exactly the same capacity as MODIS) (Newnham et al., 2015).

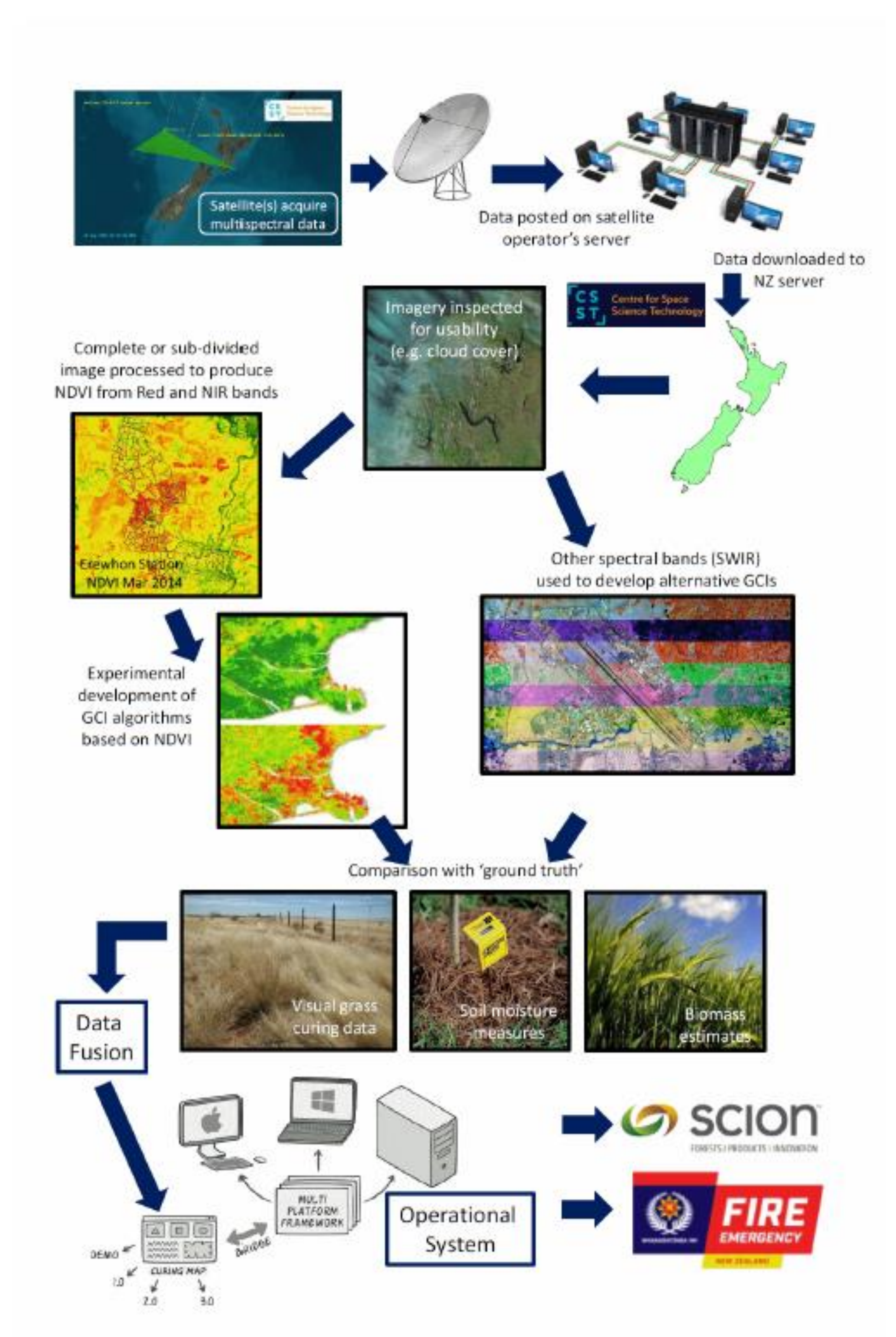


Figure 4. Work flow from satellite imagery acquisition to application in an operational system.

Hybrid model findings

If following similar strategies implemented by Australian fire agencies, New Zealand could develop a hybrid approach that combines ground and satellite data to maximise confidence in the final curing map products. This would not necessarily be tied to using existing visual field observations, or alternative measurement approaches (e.g. Levy rod). Instead, it could utilise the large network of RAWS available to FENZ and combine with observations from soil moisture probes or pasture models for ground truthing or adjusting a curing map for greater accuracy. The latter options potentially also provide a lower cost, lower maintenance approach, compared to visual estimates combined with remote sensing.

New Zealand could readily and successfully implement a satellite-based system for monitoring grassland curing over time. However, there have been a number of issues identified with relying solely on this technology. Developing a data fusion approach will maximise both the accuracy and continuity of information needed by operational fire managers. Building on strategies implemented or under trial in Australia would allow an operational system to be developed that overcomes potential gaps in data caused by persistent cloud cover or satellite instrument error, whilst also providing increased confidence in the resulting curing product by incorporating ground-observations and not relying on a single source.

As outlined above, the individual techniques of ground-based measurements and satellite imagery have their own limitations that affect accuracy of curing estimates. For this reason, Australian fire agencies have developed systems that combine field observations and satellite-derived estimates to provide more comprehensive spatial coverage. Based on conversations with operational staff from Australia, the current techniques used to assess grassland curing vary between states and territories, and include:

- The **MapVictoria model.** This is used operationally in Queensland, New South Wales, Australian Capital Territory, Victoria, Tasmania, and South Australia. The model was derived from historical MODIS satellite data and ground-based visual observations. In NSW at least, which has an extensive field observer network, the ground observations take precedence and the satellite estimates are used to extend these to areas of the state where field observations are not available. MapVictoria maps are updated by the Bureau of Meteorology every day using near real time MODIS data (Martin et al., 2015).

- The **VISCA model** is used operationally in Victoria and the Australian Capital Territory, and is used as a trial product in Queensland, New South Wales, Tasmania, and South Australia. The VISCA (Victorian Improved Satellite Curing Algorithm) maps are produced weekly by CFA, and are derived from a combination of MapVictoria satellite data and ground-based visual observations, with the satellite estimates taking precedence (Martin, et al., 2015; Wright, et al., 2016). Each jurisdiction is responsible for their own ground-based observations, which are uploaded online by fire agency personnel, and used to validate satellite curing estimates.

- The **Modified Algorithm C** is currently under trial in Western Australia (and possibly Northern Territory) by Department of Fire & Emergency Services, WA. The Modified Map C maps are updated by Landgate using MODIS data, and are validated by visual observations and NDVI data loggers. The original Map C was derived as part of the Bushfire CRC project (Newnham et al., 2010).

- **Visual Observations** are used operationally in the Northern Territory at 5-12 points. The Darwin Centre for Bushfire Research (Charles Darwin University) have collected Levy rod curing observations over several years. More recently, they have collaborated with FESA in WA over interest in the use of the Modified Algorithm C.

It is hoped that an Australian nation-wide curing product is developed and used in the near future. **NISCA (National Improved Satellite Curing Algorithm)** is a modified version of VISCA, and will combine ground-based observations with MapVictoria and Modified Algorithm C data. NISCA will use MODIS data in the interim, and will eventually use VIIRS data in the near future.

Advantages to a hybrid approach include:

- Enhancements of maps by filling in the gaps from cloud cover or satellite errors with ground observations, or through extension of ground observations with satellite data.
- Improved accuracy via validation/ground truthing of the satellite data to minimise any under- or over-estimation of curing derived from the satellite.
- Can be automated to ensure regular, objective and timely curing estimates.
- Provides a landscape scale analysis of the grassland curing state.

Disadvantages:

- Requires development of a prototype system and testing before implementation.
- Requires the FWSYS to incorporate additional data (via manual data entry of field observations, or direct entry from soil moisture or pasture modelling products).
- Requires administrators to validate the satellite data using field observations or levy rod data, which requires a network of field observers trained to collect regular, accurate ground data.

Considerations

FENZ will need to decide on how much a hybrid product is dominated by satellite data, versus how much weighting is put on ground-based observations. The NSW approach allows validation of ground-based observations with satellite estimates, with the satellite imagery being used to supplement and extend the ground observations; whereas the Victorian methodology utilises the ground observations to tune the satellite estimates.

Since FENZ desires a fully automated system, using automated ground-based estimates (e.g. from soil moisture or pasture model output) to ground-truth the satellite products and fill in any gaps of no data may be preferable. The ground observations would help minimise any under- or over-estimation of curing derived from the satellite. On the other hand, using ground observations from a network of field observers goes away from a fully automated system, but may provide more confidence in the final curing product by being based on human input, as opposed to solely automated processes.

Before going fully operationally, there will still be a need to design a field sampling program and training material for ongoing ground-based sampling to collect accurate data for use in validating the modelled estimates and/or subsequently filling in the satellite-based curing estimates in an ongoing operational system. It is essential that care be taken to identify appropriate field observers for this, and to give them sufficient hands-on training and support materials, as well as regular “refreshers” if part of an ongoing operational system.

DISCUSSION & RECOMMENDATIONS

There is a need to better estimate grassland curing as it is a key predictor of grass fire risk, including the ease of ignition, rate of spread and fire intensity. It is recognised that existing visual assessment methods used in New Zealand for monitoring grass curing are infrequently reported and subjective, and can result in poor information on grassland fire danger. Advancements in science and technologies now make it possible to take advantage of new methods or technologies to supplement or replace current curing assessments used in New Zealand.

Fire and Emergency New Zealand's aim is to have a fully automated operational system for collating and displaying grassland curing estimates to reduce the uncertainty around current inputs from erratic field observations. FENZ contracted Scion to revisit methods for assessing grassland curing, by reviewing water-balance, pasture productivity modelling and remote sensing methods. A key part is understanding the advantages and disadvantages of any new method for use in an operational grassland curing assessment system.

Over the past two decades, a considerable amount of research was carried out between Australia and New Zealand towards developing more accurate assessments of grassland curing. While visual estimates remained the operational application in New Zealand, most states within Australia have adopted a hybrid model of combining remote sensing with visual estimates.

We have carried out an in-depth investigation into several existing and new methods and technologies for assessing grass curing, and outline here the best options for FENZ in regard to these.

Direct soil moisture measurements

FENZ has now grown a good network of fire weather stations with soil moisture sensors installed across the country to warrant revisiting this approach. Out of all the methods and technologies, soil moisture sensors are the simplest and cheapest to implement to produce a Grass Curing Index (GCI). However, the spatial coverage is limited compared to remote sensing products.

In the short term, soil moisture measurements being displayed in the FWSYS can be easily set up and is already underway. A grass curing value could be estimated based on the initial relationships previously identified between the degree of curing and directly-measured soil moisture by Scion (NZ Fire Research, 2002b; Anderson & Pearce, 2003). During the up and coming fire season, these values could be validated by examination with actual grass curing values observed at the same weather station sampling sites. However, one major limiting factor would be the accuracy of visual estimates to use as a comparison against the soil moisture measurements. Another limitation is that multiple relationships may need to be developed to account for different grass species or soil types, or climate regions or fire season trends (e.g. ENSO seasons). Therefore, in the longer term, further improvements to the soil moisture-grassland curing relationship will likely need to be undertaken by investigating the effects of these and other factors outlined from the literature search. An additional advantage however is that soil moisture observations can add value to other predictions in the NZFDRS. There is also the potential to look at using the soil moisture indicators contained within the FWI System (in particular the Drought Code) to estimate grass curing.

Investigations into land environmental simulator models, which NIWA use for their forecasting, could also be used to improve accuracy of curing estimates. A coupled atmosphere-land surface model can account for various soil layers, and vegetation types and weather to forecast changes in soil moisture. They utilise the storage capacity of water in the soil layers and account for evaporation rates for different vegetation types. This option would be an alternative to using satellite-derived estimates or actual direct measurements of soil moisture. The direct measurements could be used as a starting point for running the model, with land surface model or satellite soil moisture estimates used to produce a full spatial coverage curing product. This is still some way off though, with more validation required. This would be in the next level scope for soil moisture, and would require discussions with NIWA on the best way forward.

Pasture growth/productivity models

There are several available pastoral farm decision support tools (DST) or models to help with animal production and farm management. Out of the 13 that were reviewed for application in New Zealand, three were suitable and showed promise as an operational application for use in determining grass curing. However, all three will require further validation and fine turning in the long run if chosen for implementation. Again, the limiting factors would be the accuracy of visual estimates to be used for model evaluation, along with the fact that the spatial coverage is limited compared to remote sensing products.

The AgResearch (Woodward) model would be the easiest model to implement in New Zealand because it is a simple model designed to capture curing in New Zealand. The advantages are that New Zealand has all the inputs required to get the model running and the curing output can be easily incorporated into the FWSYS. However, this model was only run for one season and is based on ryegrass/clover pastures, and will likely need fine tuning and validation to other grass types before being ready for operational application.

The Daily Bayesian Model would also suit running in New Zealand as it was designed to specifically predict grassland curing. The advantages are that this has been tested against other Australian agricultural decision support models and was more accurate. It too would be able to be developed quickly and be implemented into the FWSYS. However, it would require further field testing in New Zealand for validation and/or fine tuning to New Zealand grassland fuels before trusting it operationally.

GRAZPLAN is a more sophisticated agricultural software program compared to the above models. It has shown promise as an accurate grassland curing prediction tool in Australia. However, it is likely that considerable development would be required to either validate, adapt or develop it for use in New Zealand grass fuels. There would be the need to work with the developers to understand the assumptions and limitations of the software, along with training of how to use the software. Implementation into FWSYS would also require considerable time and money.

If a pasture model option was chosen, further investigation and development in this space would be required before it becomes a fully reliable operational system, but it could run in parallel with other options (e.g. visual observations or soil moisture). To date, no further validation of pasture models to predict curing has been carried out. This is required to improve the accuracy and ensure confidence of the system as an operation application. In particular, the water balance model and the onset of pasture reproductive development within each of these pasture models need to be fine-tuned to other grassland types.

Remote sensing

Out of the methods and technologies investigated, this is one of the best options for FENZ going forward. Remote sensing would satisfy the requirement for a fully automated system that is regular, and has full spatial coverage across the country. However, despite the considerable research undertaken to date, this option still requires a significant research component for development of a new, improved satellite-based grass curing product. This includes the need to address issues such as spatial disaggregation of coarse resolution satellite data using higher resolution bands to better match the finer resolution ground cover variability in fragmented landscapes, development and evaluation of methods to composite satellite images, and future-proofing for satellite obsolescence, through planning for transition of curing algorithms from the current MODIS instrument on the Terra & Aqua satellites to alternative replacements (such as the VIIRS instrument on the NPP satellite and upcoming JPSS satellite series).

Currently, remotely-sensed curing estimates are based on the Normalised Difference Vegetative Index (NDVI). Developing an initial prototype system, in which a Grass Curing Index (GCI) is based upon previously-trialled algorithms making use of the NDVI is expected to be straightforward. It is recognised however that improvements need to be made to the current proposed New Zealand algorithms. They require validation as they have also not been trialled operationally yet. The development of a new, improved satellite-based grass curing product therefore requires a more significant research component. Further research is suggested that could be run in parallel with an operational system, to validate and improve the accuracy of grass curing estimates from remote sensing.

Out of the 49 satellites identified, three sources of satellite data have been recommended for trialling. It is proposed that the required visible and near infra-red (VNIR) imagery can be derived from one (or more) of three satellite groups: the US NOAA JPSS constellation; the Japanese GCOM-C constellation; and the European Sentinel-3 constellation. Each of these can deliver imagery obtained at the required wavelengths, with a suitable frequency (more than once weekly), and with an adequate spatial resolution (250-375 metre pixels). Sentinel-3 appears to be the best option, based on there being two functioning satellites with GSD 300 metres. In addition, a sister constellation (Sentinel-2) offers the possibility of higher-resolution imagery which could be used to provide improved assessments of grass curing.

In the short term, a prototype system using a new satellite platform and based on previously-trialled New Zealand algorithms that make use of the NDVI could be developed. It is suggested trialling all three sources of satellite data to identify the best performing source for curing assessments. Longer term, and potentially running in parallel, further research should be conducted to validate and improve the accuracy of grass curing estimates from remote sensing. This would involve research into improving the current New Zealand curing algorithms, by fine tuning to the various grassland types, masking out other fuel types, and employing imagery at other wavelengths (other than the conventional NDVI). In addition, experiments looking into imagery at other wavelengths than the conventional NDVI (for example, the short-wave infra-red (SWIR)) could also be investigated to allow for identifying better preforming algorithms.

It is also worthy to note that there are other parameters including soil moisture content, fuel moisture, fuel type mapping, plant health, and biomass that are (or very soon) becoming accessible to measure via remote sensing. It is recommended that these options be kept in mind by FENZ and thought given to whether a preliminary study of these extra capabilities might be conducted in the future.

Hybrid model

The development of a hybrid system that combines ground and satellite data to maximise confidence in the final curing map products appears to offer the best potential to meet operational requirements. New Zealand could successfully implement a satellite-based system for monitoring grassland curing over time; however there have been a few issues identified by Australian and New Zealand researchers associated with relying solely on this technology. Developing a data fusion approach will maximise both the accuracy and continuity of information needed by operational fire managers. A satellite curing algorithm combined with ground-based observations is the best option for New Zeeland to implement and will overcome gaps in data caused by persistent cloud cover or satellite instrument error. This is the current strategy in several states of Australia and there is a move to nationalise this there for the near future.

A hybrid approach would not necessarily be tied to existing visual field observations, or alternative measurement approaches (e.g. Levy rod), but could utilise the large network of RAWS available to FENZ and combine with observations from soil moisture probes or pasture models for ground truthing or adjusting a curing map for greater accuracy. This is envisioned, as a low cost, low maintenance approach, compared to the Australian method of visual estimates combined with remote sensing.

Validation options

Field data collection during the fire season is important and provides data that will support the development of reliable operational tools for both assessing and predicting curing levels in grasslands. The field data allows for validation of the models and systems developed. FENZ have two options in this regard.

The first would be utilising existing data of curing percentages that are stored in the current FWSYS system from previous years. This options comes with its own issues, in particular the quality of data available within the FWSYS and achieving a good spread across the country. There is the acknowledged issue around the accuracy of highly subjective visual field observations. We also cannot be completely sure that the number of times where the curing values were changed throughout the fire season and how quickly the change was entered is a true and accurate representation of when the changes in grass curing actually occurred. Historically, the updating of curing values within the FWSYS has been notoriously poor. In recent times, this has been due to fire staff being unable to regularly update the curing values in the system due to being overwhelmed with the changes happening within FENZ. The suggestion here is to select regions based on those who were able to regularly adjust curing values as they occurred in the last five years.

The second option is to undertake field observations during the fire season as the prototype system is gotten up and running. This method also comes with issues for testing and evaluation. Usually there is a limit to the number of research staff available, and therefore there will be a reliance on the support of the greater network of personnel from fire and land management agencies to assist with important field data collection. It is understood that fire personnel are also stretched at times, but identifying a good spread of locations around the country is essential, and the support of local fire authorities would help validate and improve prototype curing products. Identifying major grassland types (e.g. crops, native tussock, low producing and high producing pastures) and spreading the field observation sites to encompass the various grassland types would also be beneficial for validation of the curing products.

Current field observers would likely have varying skill levels of how to assess grassland curing, and will mostly need to collect the field data with minimal supervision. It is therefore important that the data collection methods are simple and easy to follow, with comprehensive training provided to ensure accurate curing assessments are being made for use in development and validation of systems within the research project. Because training has not been run in the country for over 10 years, it suggested to seek expertise from Australia on training to carry out visual assessments to ensure the field observer network are at the same level of skill.

It is recommended that part of this validation phase would be the development of a network of trained grass curing field observers, to undertake regular field observations of grass curing to support/validate satellite estimation. A field data collection methodology and associated training package should be developed as part of this activity.

Final recommendations

Ground-based observations do not capture spatial variation in curing levels across the whole landscape. Whereas, satellite observations on the other hand can provide a curing value for every gridded cell across the country. The major issue is that satellites may not capture changes in curing in the event of consecutive days of cloud cover or satellite errors. Ultimately, satellite observations with gap filling or adjusted by ground observations (soil moisture or visual) provide the most likely means of achieving the aim of a fully automated system with maximum confidence of final curing products.

In the interim, there are likely two options for FENZ:

1. Use of soil moisture sensors to calculate a grass curing value. It is recommended, in the interim, that FENZ adopt the soil moisture method and validate this during the up-and coming fire season with visual observations from fire personnel, fine tuning the model at the end of the season if required. This is because the first stages are already underway and this could be the cheapest and least time-consuming option. A curing system could be up and running relatively much quicker than going straight to remote sensing, or using a hybrid model utilising other methods to provide ground observations (such as pasture models). However, no prototype soil moisture model exists yet, and this will need to be developed. Or,
2. Use of satellite remote sensing to provide visual daily rolling maps and tabulated data to feed into grassland fire danger rating. In the short term, FENZ can adopt the previously developed prototype system based on New Zealand algorithms that makes use of the Normalised Difference Vegetative Index (NDVI), and data from the current Terra and Aqua satellites. Again, ground truthing with visual observations from fire personnel are required for further fine tuning, as the non-automated curing maps were only trialled for one fire season previously.

In the longer term, it is also recommended to adopt the approach of the Australian fire agencies and develop a hybrid system, in parallel to the chosen interim prototype system. The development of and running of prototype satellite maps should be based on one of the two New Zealand specific algorithms recommended by Newnham et al. (2015). The prototype system, once ready for validation, could be compared and fine tuned to the already validated soil moisture sensor network and/or visual observations from local fire personnel. In the longer term, soil moisture measurements would be used to automatically fill in any gaps in the satellite data due to persistent cloud cover or satellite errors.

Finally, it is also recommended that the option for visual observations or the levy rod manual assessment technique still be present in the system, with specified users having the ability to overwrite the system if required. These manual entries could also be used to further fine tune the system and allow the algorithms to be further improved over time, and ultimately enhancing the overall curing product accuracy. A field data collection methodology and associated training package should be developed as part of this activity.

References

Alexander ME (2008). Proposed revision of fire danger class criteria for forest and rural areas in New Zealand. (2nd ed.). National Rural Fire Authority, Wellington, in association with the Scion Rural Fire Research Group, Christchurch. 62 p. [Reprint with corrections]

Alexander J, Thieme R, Kidnie S, Nichols D, Bessell R, Martin D, Chen A (2014). Use of integrated training products to support grassland curing observers. Poster presented at the AFAC & Bushfire & Natural Hazards CRC Conference 2014, 2-5 September 2014, Wellington. http://www.afac.com.au/docs/poster/use-integrated-training-products-grassland-curing.pdf

Anderson SAJ, and Pearce HG. (2003). Improved methods for the assessment of grassland curing. Conference Proceedings, 3rd International Wildland Conference, 3-6 October 2003, Sydney, Australia. 10 p. CD-ROM.

Anderson S (2004). Grassland Curing Project Report - 2003/2004. Unpublished Report. 9 p. [Scion Client Report Number 13536].

Anderson SAJ, Anderson WR, Hines F, and Fountain A (2005). Determination of field sampling methods for the assessment of curing levels in grasslands. Bushfire CRC Project A1.4, Unpublished Report. Bushfire Cooperative Research Centre, Melbourne, Australia. [Scion Client Report No. 11493]

Anon. (1993). Fire Weather Index System Tables for New Zealand. National Rural Fire Authority, Wellington, in association with the New Zealand Forest Research Institute, Rotorua. 48 p.

Arnold JE (2015). "Soil Moisture". NASA. Retrieved 15 June 2015.

Baxter GJ, and Woodward, SJR (1999). Estimating grassland curing using soil moisture indicators and a pasture quality model. In Proceedings, Australian Bushfire 99 Conference, Albury, NSW, 7-9 July, 1999. pp 33-38.

Baxter, G. 1999. Alternative techniques for estimating grassland curing as an input into fire danger modelling for New Zealand, February 1999. Forest Research, Rotorua. Forest Research Unpublished Report. [Scion Output No. 31313]

BNHCRC (2017). Soil moisture prototype improves forecasts. Bushfire and Natural Hazards CRC, Melbourne. Hazard Note Issue 32 (June 2017). http://www.bnhcrc.com.au/hazardnotes/32

Bryan JR, and Snow, VO (2008) Modelling pastoral farm agro-ecosystems: A review. *New Zealand Journal of Agricultural Research, 51*(3), 349-363.

Cheney P, Gould JS, and Catchpole WR (1998). Prediction of fire spread in grasslands. *International Journal of Wildland Fire, 8*, 1-13.

Cheney P, and Sullivan A (2008). *Grassfires: fuel, weather and fire behaviour*. Commonwealth Scientific and Industrial Research Organisation Publishing, Collingwood, VIC.

Clifford VR (2011). Grassland curing satellite assessments, New Zealand pilot trial #2. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No.18412. (June 2011). 54 p.

Clifford V, Wallace H, Pearce, G (2017). Evaluation of grass curing assessment methods for application in New Zealand. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 23582. 26 p.

CliFlo (2018).The National Climate Database. https://cliflo.niwa.co.nz Retrieved 10 May-2018.

CSIRO (2007). Grassgro brochure. Produced by CSIRO Plant Industry Communication Group. http://www.GRAZPLAN.csiro.au/files/brchr_grassgro.pdf

Czarnomski NM, Moore GW, Pypker TG, Licata J, and Bond BJ (2005). Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest. *Canadian Journal of Forest Research, 35*, 1867-1876.

Daily HG (2012). Development of pasture growth models for grassland fire danger risk assessment. PhD thesis, University of Tasmania.

Daily HG, Lane PA, Lisson SN, Bridle KL, Anderson SAJ, Corkrey R (2013). Leaf growth and senescence rates of three pasture grasses and wheat. *Crop and Pasture Science, 64*, 660-672.

Dharssi I, and Vinodkumar, K (2015). Sources of soil dryness measures and forecasts. Bushfire and Natural Hazards CRC poster.

Dharssi I, Bovis KJ, Macpherson B, and Jones CP (2011). Operational assimilation of ASCAT surface soil wetness at the Met Office. *Hydrology and Earth System Science, 15*, 2729-2746.

Doherty JJ, Anderson SAJ, and Pearce HG (2008). An analysis of wildfire records in New Zealand: 1991-2007. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 12789. 194 p.

Donnelly JR, and Moore AD (1997). Decision support: delivering the benefits of grazing systems research. Grazing Systems Ecology, Session 26.

Donnelly JR, Moore AD, and Freer M (1997). GRAZPLAN: Decision support systems for Australian grazing enterprises. I. Overview of the GRAZPLAN project, and a description of the MetAccess and LambAlive DSS. *Agricultural Systems, 54*(1), 57-76.

Edaphic Scientific (2018). The soil water compendium. http://www.edaphic.com.au/5-common-mistakes-when-measuring-soil-moisture/

Garvey M (1997). A strategy to improve grassland curing information. Notes from a Grassland Curing Workshop, Aspendale, Melbourne, August 1997.

Gill M (1999). Fire danger, grass curing and fuel management. Firebreak, Research Letter No. 15, October 1999. (available at http://www.esb.act.gov.au/firebreak/resletter15.html).

Gill AM, King KJ, and Moore AD (2010). Australian grassland fire danger using inputs from the GRAZPLAN grassland simulation model. *International Journal of Wildland Fire, 19*(3), 338-345.

Hanrahan L, Geoghegan A, O'Donovan M, Griffith V, Ruelle E, Wallace M, and Shalloo L (2017). PastureBase Ireland: A grassland decision support system and national database. *Computers and Electronics in Agriculture, 136*, 193-201. doi:10.1016/j.compag.2017.01.029

Höglind M, Van Oijen M, Cameron D, and Persson T. (2016). Process-based simulation of growth and overwintering of grassland using the BASGRA model. *Ecological Modelling, 335*, 1-15.

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann, NI, et al. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software, 62*, 327-350.

Hosking R (1990) Grassland curing index – a district model that allows forecasting of curing. *Mathematical and Computer Modelling. 13*, 73-82.

Jégo G, Bélanger G, Tremblay GF, Jing Q, and Baron VS (2013). Calibration and performance evaluation of the STICS crop model for simulating timothy growth and nutritive value. *Field Crops Research, 151*, 65-77. doi:10.1016/j.fcr.2013.07.003

Jing Q, Bélanger G, Baron V, Bonesmo H, Virkajärvi P, and Young D (2012). Regrowth simulation of the perennial grass timothy. *Ecological Modelling, 232*, 64-77.

Johnson IR, and Thornley JHM (1982). A model of grass growth. The Grassland Research Institute, Hurley, Maidenhead, Berkshirt. *Annals of Botany, 51*, 599-609.

Martin D, Chen A, Nichols D, Bessell R, Kidnie S, and Alexander J (2013), An automated operational system for collating field and satellite data for grassland curing assessment. Paper presented at the Research Forum of the Bushfire Cooperative Research Centre, Melbourne, Victoria, Australia, 21 p. http://www.bushfirecrc.com/sites/default/files/managed/resource/martin_and_chen.pdf

McCall DG, and Bishop-Hurley GJ (2003). A pasture growth model for use in a whole-farm dairy production model. *Agricultural Systems, 76*(3), 1183-1205.

Moore AD, Donnelly JR, and Freer M (1997). GRAZPLAN: Decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. *Agricultural Systems, 55*(4), 535-582.

Nature Education (2012). https://www.nature.com/scitable/content/generalized-relationship-between-soil-texture-classes-and-59719652

Newnham GJ, Grant IF, Martin DN, and Anderson SAJ (2010). Improved methods for assessment and prediction of grassland curing: Satellite based curing methods and mapping - Final Report: Project A1.4. Bushfire Cooperative Research Centre, Report No. A.11.10. Bushfire Cooperative Research Centre, Melbourne.

Newnham G, Clifford VR, Pearce G, Grant I, Wood S, Uddstrom M (2015). New Zealand grassland curing satellite algorithms development and mapping system implementation. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 22828. (June 2015). 55 p.

Czarnomski NM, Moore GW, Pypker TG, Licata J, and Bond BJ (2005). Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest. *Canadian Journal of Forest Research, 35*, 1867-1876.

NIWA (2016a). New Zealand Drought Index and Drought Monitor Framework. National Institute of Water and Atmospheric Research, Wellington. NIWA Client Report. https://niwa.co.nz/sites/niwa.co.nz/files/NZDI_more_info.pdf

NIWA (2016b). Soil Moisture Deficit (SMD). https://www.niwa.co.nz/climate/nz-drought-monitor/droughtindicatormaps/soil-moisture-deficit-smd

NIWA (2016c). Daily climate maps. https://www.niwa.co.nz/climate/daily-climate-maps

NIWA (2016d). Climate information and resources. Average soil moisture deficit onset and termination maps. https://www.niwa.co.nz/climate/information-and-resources/drought/firstandlastdeficitmaps

NIWA (2016e). Virtual Climate Station data and products. https://www.niwa.co.nz/climate/our-services/virtual-climate-stations Retrieved 10 May-2018.

NZ Fire Research (2002a). Fire Research Update. Newsletter of the forest and rural fire research Programme, New Zealand Forest Research Institute, Rotorua. (March 2002).

NZ Fire Research (2002b). Fire Research Update. Newsletter of the forest and rural fire research Programme, New Zealand Forest Research Institute, Rotorua. (June 2002).

Ochsner TE, Cosh MH, Cuenca RH, Dorigo WA, Draper CS, Hagimoto Y, Kerr YH, Njoku EG, Small EE, Zreda M, and Larson KM (2013). State of the art in large-scale soil moisture monitoring. *Soil Science Society of America Journal, 77*, 1888-1919. doi:10.2136/sssaj2013.03.0093

O'Geen AT (2013). Soil water dynamics. *Nature Education Knowledge, 4*(5), 9.

Penney AC (1997). Climate database (CLIDB) user's manual. 4th ed. National Institute of Water and Atmospheric Research, Wellington. NIWA Technical Report 4.

PSS (2018). Physical properties of soil and soil water. Plant and Soil Sciences eLibrary. https://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447039&topicorder=10&maxto=10 Retrieved 10 May-2018.

Ray RL, Fares A, Yiping H, and Temimi M (2017). Evaluation and inter-comparison of satellite soil moisture products using in situ observations over Texas, U.S. *Water, 9*(6), 1-22.

Rudnick DR, Irmak S, Haghverdi A, Burr CA, Haver TM, and Dorr TJ (2016). Soil water sensor for irrigation management. University of Nebraska. Nebraska Extension. http://extensionpublications.unl.edu/assets/pdf/ec3002.pdf

Romera AJ, Beukes P, Clark C, Clark D, Levy H, and Tait A (2010). Use of a pasture growth model to estimate herbage mass at a paddock scale and assist management on dairy farms. *Computers and Electronics in Agriculture, 74*(1), 66-72. doi:10.1016/j.compag.2010.06.006

Sample DJ, Owen JS, Fields JS, and Barlow S (2016). Understanding Soil Moisture Sensors: A Fact Sheet for Irrigation Professionals in Virginia. College of Agriculture and Life Sciences. Virginia Tech. Publication BSE-198P. https://pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/BSE/BSE-198/BSE-198-PDF.pdf

Scotter DR, Clothier BE, and Turner MA (1979). The soil water balance in a fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research, 17*, 455-465.

Su C, Ryu D, Young R, Western WA, and Wagner W (2013). Inter-comparison of microwave satellite soil moisture retrievals over the Murrumbidgee Basin, southeast Australia. *Remote Sensing of Environment, 134*, 1-11.

Thornley JHM, and Johnson IR (2000). Plant and Crop Modelling. A Mathematical Approach to Plant and Crop Physiology. [Reprint of 1990 edition] ISBN 1-930665-05-9. 669 p.

Trial PJ, Abaye AO, Thompson TL, and Thomason W (2015). Conservation Agriculture in Senegal: Comparing the Effects of Intercropping and Mulching on Millet Yields. Thesis for Master of Science, New Mexico State University Climate Centre.

Van Wagner CE (1987). Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario. Forestry Technical Report 35. 37 p.

Vinodkumar, and Dharssi I (2017). Evaluation of daily soil moisture deficit used in Australian forest fire danger rating system. Bushfire and Natural Hazards CRC, Melbourne. 32 p.

Vinodkumar, Dharssi I, Bally J, Steinle P, McJannet D, and Walker J (2017). Comparison of soil wetness from multiple models over Australia with observations. *Water Resources Research, 53*, 633-646.

Vogeler I, Mackay A, Vibart R, Rendel J, Beautrais J, and Dennis S (2016). Effect of inter-annual variability in pasture growth and irrigation response on farm productivity and profitability based on biophysical and farm systems modelling. *Science of the Total Environment, 565*, 564-575. doi:10.1016/j.scitotenv.2016.05.006

Woodward SJR McCall DG, and Barker DJ. (1998). Pasture Quality model summary - 16 December 1998. AgResearch Unpublished Report.

Woodward, S (2001). Validating a model that predicts daily growth and feed quality of New Zealand dairy pastures. *Environment International, 27*, 133-137.

Wright D, Chen A, Bessell R, Kidnie S, Nichols D, Slijepcevic A (2016). Reducing inconsistencies of grassland curing assessment between multiple jurisdictions across australia. Proceedings of the 5th International Fire Behaviour and Fuels Conference, April 11-15, 2016, Melbourne, Australia.

Yang Y, Uddstrom M, Revell M, and Moore S (2014). Soil moisture simulation by JULES in New Zealand: verification and sensitivity tests. *Meteorological Applications, 21,* 888-897. doi: 10.1002/met.1426

Yang Y, Uddstrom M, Pearce G, and Revell M (2015). Reformulation of the Drought Code in the Canadian Fire Weather Index System implemented in New Zealand*. Journal of Applied Meteorology and Climatology, 54*(7), 1523-1537.

Yebra M, Dennison PE, Chuvieco E, Riano D, Zylstra P, Hunt Jr, E, Danson F, Qi Y, and & Jurdao S (2013). A global review of remote sensing of live fuel moisture content for fire danger assessment: moving towards operational products. *Remote Sensing of Environment, 136*, 455-468; doi:10.1016/j.rse.2013.05.029.

APPENDIX A. Summary of possible methods

Table Key:

🟩	Good	🟦	Bad
🟨	Fair	▨	Unknown

Table 1: An evaluation of the advantages or disadvantages of potential international grassland curing assessment methods (Source: reproduced from Clifford et al., 2017).

Curing assessment	Accuracy	Frequency	Training	Workload	Costs	Technology limitations	Scale	Other requirements	Practicality	Ease of linking	Overall ranking
Destructive sampling of grass	Accurate	Weekly/ fortnightly/ monthly	YES. Moderate. Before the fire season	High. Very labour intensive	High. Ongoing personnel hours involved	None	Localised	Transportation, sampling tools, oven drying.	Not practical to implement on a large scale	Can be easily linked. Manual entry	Low
Non-destructive Levy rod technique	Somewhat. Requires refinement	Weekly/ fortnightly	Yes. Moderate. Before the fire season	High. Labour intensive	High. Ongoing personnel hours involved	None	Localised	Transportation, sampling tools.	Not practical to implement on a large scale	Could be easily linked. Manual entry	Low
Height/cover correlations	Somewhat. Requires refinement	Weekly/ fortnightly	YES. Moderate. Before the fire season	High. Labour intensive	High. Ongoing personnel hours involved	Still in research evaluation phase	Localised	Transportation, sampling tools.	Not practical. Would be time consuming	Could be easily linked. Manual entry	Low
Fuel moisture content correlations	Somewhat. Requires refinement	Weekly/ fortnightly	YES. Moderate. Before the fire season	High. Labour intensive	High. Ongoing personnel hours involved	Still in research evaluation phase	Localised	Transportation, sampling tools, drying or FMC measurement	Not practical. Would be time consuming	Could be easily linked. Manual entry	Low
Pasture growth models	Somewhat/ requires refinement	Daily	None. Would be computer generated	None. Automated	Low. After an initial cost of set up	Still in research evaluation phase	Medium	Limited to certain pasture types	It has merit. Practical	Could be easily linked. Manual entry	Medium
Climatology Soil probes	Accurate	Daily	None. Would be computer generated	None. Automated	Low. After an initial cost of set up	Still in research evaluation phase	Medium	Requires fit out and maintenance of soil probes onto RAWS	It has merit. Practical	Could be easily linked. Manual entry	Medium
Climatology DC correlations	Somewhat/ requires refinement	Daily	None. Would be computer generated	None. Automated	Low. After an initial cost of set up	Still in research evaluation phase	Medium	Different DC relationships for each region	It has merit. Practical	Could be easily linked. Manual entry	Medium
Visual assessments from the car	Not accurate	Weekly/ fortnightly	Not recommended	Low	Low	None	Localised	Strong advise against doing this	Not practical due to inaccuracies	Already linked. Manual entry	Low
Visual assessments walking in the field (CURRENT)	Somewhat, subjective	Weekly/ fortnightly	Yes. Moderate. Before the fire season	Moderate	Moderate. Ongoing due to personnel hours involved	None	Localised	Transportation, photo guide, and regular training. Identify correct personnel for this role.	Practical. Is simple, but frequency is not being meet due to personnel workloads	Already linked. Manual entry	Medium
Photography Hand held devices	Untested in NZ	Weekly/ fortnightly	YES. Moderate. Before the fire season	Moderate	Moderate. Ongoing personnel hours involved	Still in research evaluation phase	Localised	Purchase of hand held cameras	It has merit	Would require some time to link, from a computer or manual entry	Low

Table 1. Continues

Curing assessment	Accuracy	Frequency	Training	Workload	Costs	Technology limitations	Scale	Other requirements	Practicality	Ease of linking	Overall ranking
Hand-held spectrometry	Untested in NZ	Weekly/ fortnightly	YES. Moderate. Before the fire season	Moderate	Moderate/high. Ongoing personnel hours involved	Still in research evaluation phase	Localised	Purchase of lidar/laser scanning sensors	It has merit. Not currently practical due to expensive tech	Would require some time to link, from a computer or manual entry	Low
Photography Web cameras	Untested in NZ	Daily	None. Would be computer generated	None. Automated	Moderate. After an initial cost of set up	Yet to be tested. Field of view and time of day issues.	Medium	Purchase of good quality digital web cameras	It has merit. Practical, but would require a unit for each RAWS	Requires time to link via computer. This would increase set up costs	Medium
Stationary spectral sensors	Untested in NZ	Daily	None. Would be computer generated	None. Automated	Moderate/high. After an initial cost of set up	Yet to be tested	Medium	Purchase of sensors maybe expensive	It has merit. Practical, but would require many units	Requires time to link via computer. This would increase set up costs	Low
Mobile spectrometry Autonomous rover systems	Untested in NZ	Daily	None. Would be computer generated	None. Automated	Moderate/high. After an initial cost of set up.	Yet to be tested	Medium	Purchase of rovers and maintenance	It has merit. Practical, but would require a number of units	Requires time to link via computer. This would increase setup costs	Low
Mobile spectrometry Autonomous UAV	Untested in NZ	Weekly/ fortnightly	Low/Medium depending on CAA rules. This could be computer generated, or piloted which requires training	Low or medium depending on CAA rules	Moderate/high. After an initial cost of set up. And ongoing due to personnel hours involved (if pilots involved)	Yet to be tested	Medium	Purchase of UAV, ongoing maintenance and repairs, extra batteries, pilot training. Depending on the camera(s) involved, these are also costly	It has merit. May not be practical as would require a number of units and is expensive tech	Requires time to link via computer	Low
Satellite imagery	Somewhat/ requires refinement	Daily/weekly/ fortnightly. Depends on chosen satellite & compositing period	None. Would be computer generated	None. Automated	Low/moderate. Satellite data is free, just requires initial cost for setting up image processing algorithms & incorporation into FWSYS	If you lose satellite/data links, you have no data. Affected by resolution of satellite, snow & cloud cover. Also time & frequency of pass over NZ	Landscape	Would require a year of evaluation. MODIS is eventually being replaced by VIIRS (which could penetrate cloud cover). Also Himawari.	Practical. It is already running in Australia and has been trialled in NZ	Requires time to link via computer. This would increase the set up costs	Medium
Combination of visual and satellite observations	Somewhat. Improvement on just satellite tech alone	Daily/weekly/ fortnightly. Depends on chosen satellite	Yes. Moderate. Before the fire season	Low/ moderate	Moderate. After an initial cost of set up. Ongoing due to personnel hours involved	As above with satellite alone, however ground observations can fill in gaps	Landscape	Would require a year of evaluation.	Practical. It is already running in Australia (Vic & NSW)	Requires time to link via computer. This would increase the set up costs	Medium

APPENDIX B. Soil moisture background

Soil moisture, or soil water content, has a direct influence on the growth and moisture content of grasses (Scotter et al., 1979). Soil moisture is the water that is held in the spaces between soil particles. Surface soil moisture is the water in the upper 10cm of soil, and root zone soil moisture is considered to be in the upper 200cm of soil, which is generally available to plants Arnold (2015). Soil moisture content will increase (positive change in storage) when the inputs (rainfall or irrigation) exceed the outputs. Soil moisture content will decrease when the outputs (such as percolation, surface runoff, evapotranspiration) exceed the inputs. We can assume that, if the soil water content has been below wilting point for a month or more that grass is pretty much dead.

The ability for soil to hold and transport water is due to the differences in soil physical and chemical properties. Soil can act like a sponge and either take up or loose water. The movement of water is called infiltration, and the downward movement is called percolation. The pore space in soils is what allows water to infiltrate and percolate. Water can move rapidly through soil at a high water content, mainly because of the downward pull of gravity and the high hydraulic conductivity of nearly saturated soil. However, the hydraulic conductivity decreases rapidly as water drains through the soil and the rate of movement eventually slows. Soil moisture is most critical between two points: **Field capacity** (FC) and **permanent wilting point** (PWP) – both representing the upper and lower limits of a soil's ability to hold water.

Water that is held in a soil is described by the term "water content". Several terms are used to describe water contents (PSS, 2018)*:*

- Soils are considered **saturated** when all the pores are filled with water (soils are at their wettest).
- **Field capacity** is defined as the condition that exists after a saturated soil is allowed to drain to the point where the pull of gravity is no longer sufficient to remove any additional water. Soils are said to be at field capacity when soil has been saturated and allowed to drain up to 48 hours.
- **Permanent wilting point** is the soil water content when plants have extracted all the water they can. At this point, a plant will wilt and not recover. Permanent wilting does not mean that the plant is killed by water potentials in this range. It means that the plant will not recover from wilting unless water is applied
- **Unavailable water** volumetric water content measured is the total amount of water held in a given soil volume at a given time. It includes all water that may be present including gravitational, available and unavailable water. Is the soil water content that is strongly attached to soil particles and cannot be extracted by plants (soil is at its driest).
- **Gravitational water** refers to the amount of water held by the soil at saturation and field capacity
- **Water holding capacity** is the amount of water between field capacity and wilting point.
- **Plant available water (PAW)** is the amount of moisture available for plant uptake. It is the portion of water holding capacity that can be absorbed by a plant. Plant available water is defined as the water held in the soil between field capacity and permanent wilting. It is generally considered to be 50% of the water holding capacity.
- **Volumetric water content** is the total amount of water held in a given soil volume at a given time. It includes all water that may be present including gravitational, available and unavailable water.

Soil moisture alone would not provide a complete description of water status for curing. It would be better to include PAW (Plant Available Water). **Plant available water** is described by using two moisture content levels (**field capacity and permanent wilting point**) are often used to indicate the upper and lower limits of plant available water (O'Geen, 2013).

Soil types and soil texture will likely vary by depth, and so does water holding capacity and plant available water holding capacity (PAW). Therefore it will also be important to understand the soil profile when investigating soil moisture relationships. Medium textured soils (such as fine sandy loam, silt loam and silty clay loam) have the highest water holding capacity, while coarse soils (sand, loamy sand and sandy loam) have the lowest water holding capacity (Figures 1 & 2).

Soil moisture maps

In New Zealand, drought is monitored using four common indices by the National Institute of Water and Atmospheric Research Ltd. (NIWA) (NIWA, 2016a):

- the Standardised Precipitation Index (SPI), which relates to precipitation;

- the Soil Moisture Deficit (SMD), plus its anomaly (SMDA), which relate to available water in the soil; and
- the Potential Evapotranspiration Deficit (PED), which relates to loss via evapotranspiration.

The soil moisture deficit and the anomaly maps are useful and complementary indices for agricultural industries (especially pasture growth) as they are directly related to soil moisture (Figure 4 & 5) (NIWA, 2016b). Soil moisture deficit is a term used in New Zealand to describe the amount of water that the system is short of full capacity. The value of soil moisture deficits can range from 0 (soil holds water to full capacity) to total capacity (when the soil is completely dry). Daily soil moisture content (mm) is calculated using a water balance model, based on daily rain (mm), daily potential evapotranspiration (PET, mm) and a fixed available water capacity (the amount of water in the soil 'reservoir' that plants can use) of 150 mm (NIWA 2016b).

NIWA uses a simple water balance model and assumes a fixed soil moisture capacity of 150 mm of water, based on a typical loam soil. This is assumed as it’s the typical root zone for pasture in medium silt-loam soil. The value of SMD depends on the SMD value from yesterday, and increased by the amount of water lost to evapotranspiration and diminished by the amount of precipitation that has fallen. Soil moisture deficits indicate dryness. A high SMD value can be the result of either a short spell of very dry conditions or of a longer spell of moderately dry conditions. In wet conditions the deficit will go down to 0, which means full capacity is reached and any extra precipitation will be lost as runoff (NIWA, 2016b).

Note: Potential evapotranspiration, commonly abbreviated to PET, is the expected amount of water that would be evaporated and transpired if all that water is available. The difference between potential evapotranspiration (PET) and actual evapotranspiration is called the Potential Evapotranspiration Deficit, commonly abbreviated as PED. PED can be thought of as the amount of water needed (either as irrigation or rainfall) in order to keep pastures growing.

NIWA can produce soil moisture maps using daily gridded data from the Virtual Climate Station Network (VCSN) and a thin-plate smoothing spline model to carry out spatial interpolations of soil moisture across the country. The VCSN estimates are produced daily based on actual data observations located around the country. The estimates include daily rainfall, potential evapotranspiration, air and vapour pressure, maximum and minimum air temperature, soil temperature, relative humidity, solar radiation, wind speed and soil moisture on a regular (~5km) grid covering the whole of New Zealand (NIWA, 2016e).

NIWA produces a range of drought indicator maps for the country and display these on their public website. These include daily soil moisture deficit (SMD) and soil moisture anomaly maps. The SMD map shows the historical soil moisture deficit for the date in question, for the same time last year, and for the current soil moisture deficit. The anomaly map shows the difference between the current and historical soil moisture deficits (NIWA, 2016b,c,d).

Land surface models (LSMs)

Soil moisture can vary over short distances and time so that measurements made at one location may not be relevant to neighbouring locations. The variability in soil moisture is due to the distribution and characteristics of precipitation, soil texture, vegetation and topography. This spatial variability limits the effectiveness of ground based point observations of soil moisture. Currently, no extensive global soil moisture observation network exists. However, Land surface models (LSMs) and advancements in remote sensing are showing promising results in soil moisture estimates.

Land surface models (LSMs) are capable of estimating soil moisture more thoroughly than empirical methods (Dharssi et al., 2012). LSMs can be complex models that can be used separately or as part of general circulation models to investigate hydrological cycles between the soil-plant-atmosphere on the earth’s surface. These models could account for plant physiology, vegetation dynamics and groundwater dynamics.

Several studies have investigated the effectiveness of remote sensing in providing accurate estimates of soil moisture at the surface soil layers (Dharssi et al., 2011; Ochsner et al., 2013; Ray et al., 2017; Su et al., 2013). These studies also indicate reasonable or improved results in estimating and forecasting soil moisture at larger scales.

Remotely sensed soil moisture

This Bushfire & Natural Hazards CRC project addressed a significant limitation in the ability to accurately estimate soil moisture. Vinodkumar & Dharssi (2017) believe that the current traditional drought indices under predict soil dryness. The traditional indices are simplified water balance models driven by daily rainfall and temperature that tend to oversimplify factors that influence soil moisture (Vinodkumar & Dharssi, 2017; Vinodkumnar et al., 2017).

They developed a prototype, high-resolution soil moisture analysis system called JASMIN to improve fire danger forecasting and operational fire behaviour predictions (BNHCRC, 2017). JASMIN is based on satellite measurements and advanced physics-based models, for use in fire danger prediction systems. JASMIN has a spatial resolution of 5km, and can predict surface soil moisture, which is closely related to dead-fuel moisture content and root-zone soil moisture. The results from this study suggest that the accuracy of soil moisture can be greatly improved by using physically based land surface models. The next steps are to improve the spatial resolution further to 1km and utilise the NASA Land Information System to boost the number of measurements.

The results from this work are encouraging. However the outputs from this system would need to be calibrated to the New Zealand environment before they could be adopted into the FWSYS. A pilot project would need to be run, where the JASMIN model outputs were verified against ground-based soil moisture observations or fuel moisture readings from direct measurements at weather stations.

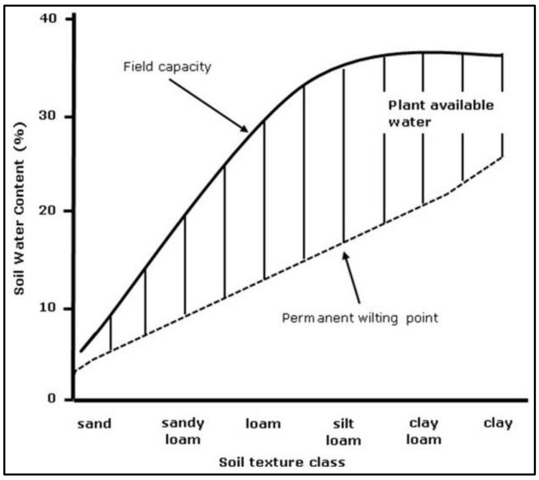


Figure 5. A generalised relationship between soil texture classes and plant available water holding capacity (PAW). Source: Nature Education, 2012.

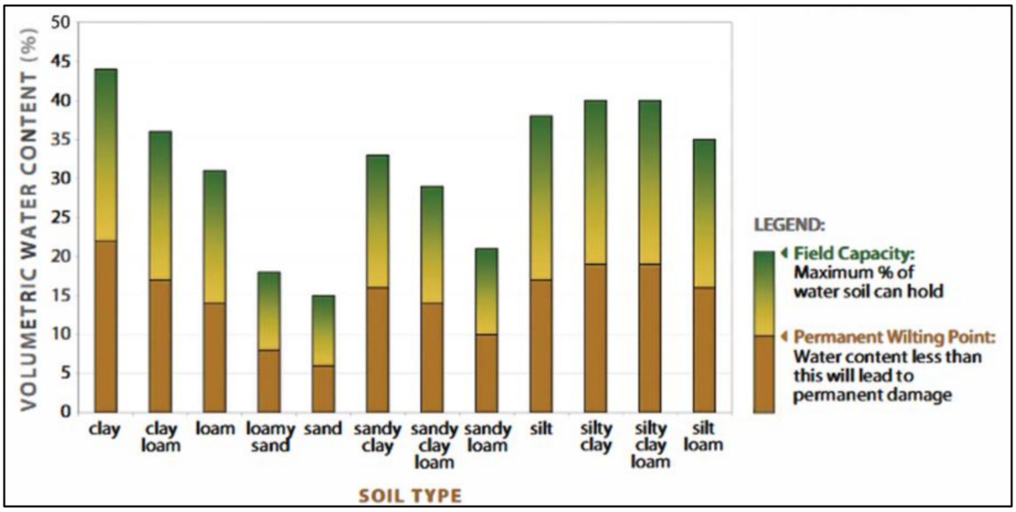


Figure 6. Water holding capacity by soil type. Source: Trial, et al., 2015

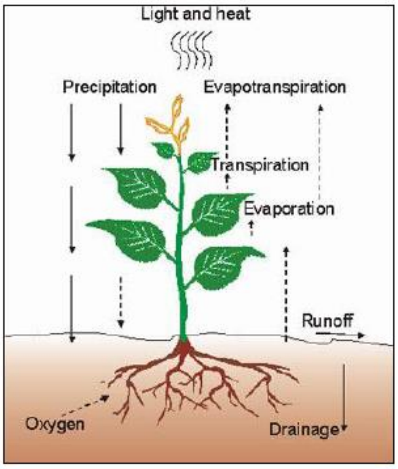


Figure 7. Water balance process. Source: NIWA

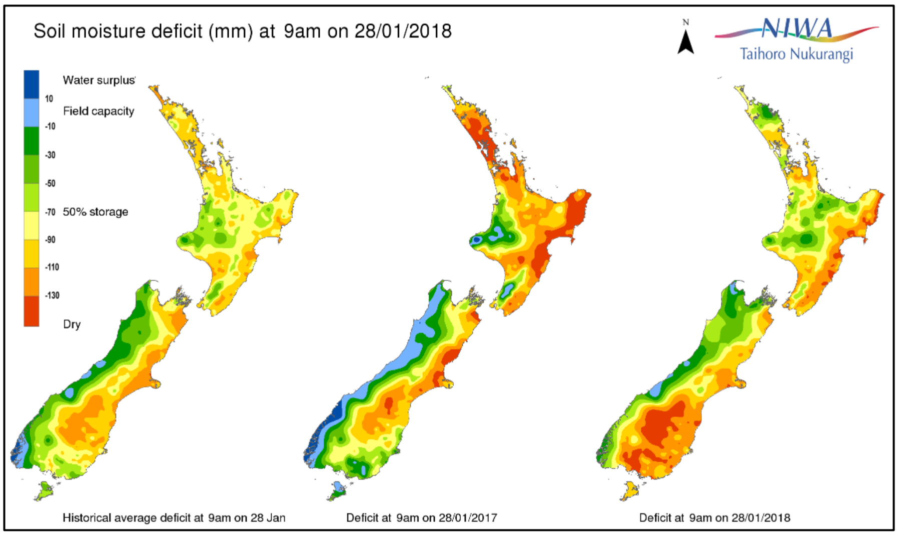


Figure 8. Example Soil Moisture Deficit (SMD) map for New Zealand, showing the historical mean (left map), the SMD one year ago (middle map), and the current SMD (right map). Source: NIWA, 2016c.

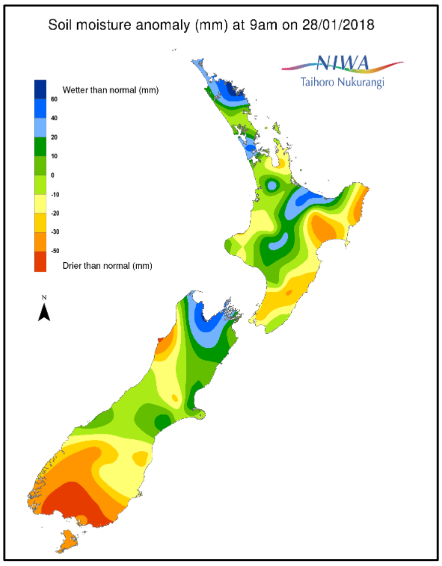


Figure 9. Example Soil Moisture Deficit Anomaly map (difference from normal) for New Zealand. Source: NIWA, 2016c.

Measuring soil moisture and sensor types

Direct measurements for quantifying soil water status are destructive, tedious and time consuming, expensive and non-continuous in nature. As a result, several technologies have been developed to estimate soil water status. These sensors are “indirect” soil water monitoring methods, which means they don’t directly measure soil water status but estimate it based on properties using a factory calibration equation.

Soil moisture sensors are not just used for research applications in climate and environmental sciences, but also for agricultural applications, to help farmers manage irrigation more effectively and improve soil moisture during plant growth.

There are a range of sensors for measuring soil moisture, as well as other layers within the soil profile (e.g. duff moisture probes). Many of these sensors can be purchased through Scottech, Harvest and other sites. The neutron probe is regarded as the best technology for soil moisture, however it is very expensive and not suitable for remote monitoring. Time domain is the next best option for measuring soil moisture. Correct installation is key to getting good data from soil probes. International best practise for measuring soil temperature and moisture is a depth of 100mm.

The types of soil moisture products available are listed below, and detailed descriptions including their advantages and disadvantages are located in the pages overleaf.

- Tensiometers
- Gypsum blocks
- Neutron gauge
- Time Domain Reflectometry sensors (TDR)
- Time Domain Transmission sensors (TDT), i.e. Aquaflex
- Capacitance sensors or Frequency Domain Reflectometry (FDR)

There are two classes of soil moisture/water content sensors, those that:

(1) measure soil water potential,
(2) estimate volumetric soil water content.

Soil water potential sensors include gypsum blocks and tensiometers. Soil water content sensors include capacitance or time domain sensors. The output from these two types is very different.

- Soil water potential reflects the amount of energy available for a plant to extract water from the soil, measured in kilopascals or pF. It is also not affected by the physical properties of soils. So a temperature measurement in sand or clay is the same.
- Soil water content is how much water there is in a given amount/volume of soil, expressed as a percentage. Water content is dependent on the physical properties of soils. Commercial sensors have a default percentage value based on a generic calibration curve. The real output will depends on the type of soil your sensor is installed in. It is important to calibrate these sensors!

The amount of water or moisture in soil can be measured as either gravimetric soil water content (GWC) or volumetric soil water content (VWC).

- Soil moisture measurements via the direct gravimetric measurement involve removing, drying and weighing samples. GWC is the mass of water per mass of dry soil in a given sample.
- Generally, soil moisture sensors produce an output that registers volumetric water content (VWC), typically expressed as a percentage. VWC is the volume of water per volume of soil. The output value is not a true reflection of actual water content but an estimation. The volumetric water content is measured indirectly utilising soil properties (such as electrical resistance, dielectric constant, or interaction with neutrons). Soil moisture measurements should be calibrated as the measurements could vary depending on soil type, temperature or electric conductivity.

Tensiometers

A measuring device to determine the soil water potential. Typically a manual method to track soil moisture status. Typically used by farmers and gardeners. A tensiometer measures how much tension is in the water when it comes into contact with the soil. The drier the soil the higher the tension. The tensiometer is buried in the soil, has a pressure gauge, and a hand pump is used to create a vacuum. It is considered to be in equilibrium with the soil water.

- As soil dries, water is sucked from the tube into the soil causing a suction gradient, the vacuum in the tensiomerter increases, which is detected by the gauge.
- If the soil is wet, the soil has a greater water pressure than that of the tensiometer, the vacuum inside the tube pulls moisture from the soil and water will diffuse into it.

Advantages	Disadvantages
It’s cheap	Needs to be manual collected and manual reset
Measures soil water potential, which is more relevant to plant stress and easy to interpret	Operating range is not extended as well to dry soils
	Limited range

Sites:

- http://www.edaphic.com.au/products/soils/tensiometers/
- http://www.edaphic.com.au/products/soils/soil-columns-tensiometers/
- http://www.pdlord.co.nz/tentek-tensiometers.php
- https://www.youtube.com/watch?v=FDKqEYoG_XQ

Gypsum blocks

Also measures soil water potential. It is composed of a porous material with contains two electrodes. The porous structure allows water to move in and out of the block with the immediate soil. The water in the soil will reach an equilibrium with the block and the electrical resistance is determined and relates to soil water potential.

Advantages	Disadvantages
It’s cheap and easy to use	Not accurate for wet soils
Measures soil water potential, which is more relevant to plant stress and easy to interpret	Blocks will dissolve over time. Will need replacing every 2-4 years (depending on soil condition)
Can be logged with soil moisture trend displayed over time	relatively small sphere of influence

Sites:
http://www.frizzell.co.nz/irrigationmoisture/soil-moisture-sensor
http://www.naturalresources.sa.gov.au/samurraydarlingbasin/publications/gypsum-blocks-for-irrigation-management

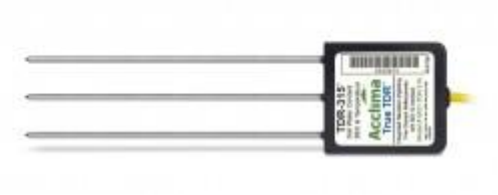
Neutron probes

The neutron probe measures soil water content from sequential depths. It contains radioactive material, which activated releases a known number of neutrons. The probe can calculate the speed of the neutrons, as they collide with hydrogen contained in water molecules in the soil, they slow down.

Advantages	Disadvantages
The most robust, accurate method of soil water content measurement.	Manual reading
Measures a large volume of soil.	Needs to be calibrated to specific soil type
Not affected by temp, or pH	Expensive to purchase

Sites:
http://www.naturalresources.sa.gov.au/samurraydarlingbasin/publications/neutron-probes-and-soil-moisture
http://www.ictinternational.com/products/soils/moisture-sensors/

Time Domain Reflectometry (TDR)



After capacitance, this is the next widely used sensor. This sensor uses a small electrical device connect to small parallel rods that are inserted into the soil. It measures the time taken for an electromagnetic pulse to travel down the rods when surrounded by soil. The rods are usually about 5 mm in diameter and normally no longer than 70 cm. It measures the soil water content independently of other soil variable (density, texture, temperature and electrical conductivity).

Advantages	Disadvantages
Good accuracy	Need different length rods to get measurements for different depths.
Large measurement volume	Good contact with the soil is critical. Any air gaps will lead to erroneous measurements.
Doesn’t require calibration to specific soils. However accuracy is reduced. Not as easily influenced by saline soils.	Should not be used in high saline soils or soils with high bulk electrical conductivity or high attenuation.
	Small sensing area
	May need recalibration for soils with tightly held water

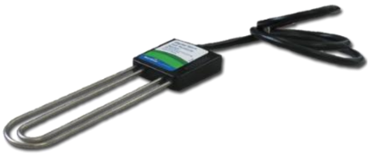
Sites:
http://www.ictinternational.com/products/soils/moisture-sensors/
http://www.edaphic.com.au/soil-water-compendium/time-domain-reflectometry-tdr/

Capacitance meters (FDR or frequency domain reflector)
The most widely employed method to measure soil water content is capacitance. It can sometimes be referred to as frequency domain. These sensors come in a range of forms from buried sensors connected to a data logger or portable. These devices measure soil water content. These sensors work by generating an electromagnet field. The amount of water in the soil will affect the capacity to transmit electromagnetic waves. Their high sensitivity, lack of robustness and calibration problems have limited their use in the field to date.

Advantages	Disadvantages
Continuous recording.	Relatively expensive.
Can display trends in soil water on the computer screen	small sphere of influence
Can monitor multi depths at once	Difficult in rocky/sandy/shallow soil
Accurate once calibrated to soil	Portable systems are manual measurements
Can be used in saline soils	Must be calibrated to soil type
Less expensive than TDRs	More sensitive to temperature and soil density
Less noise than TDR	Need good contact with soil. Sensitive to air gaps

Sites:
http://www.ictinternational.com/products/soils/moisture-sensors/
http://www.naturalresources.sa.gov.au/samurraydarlingbasin/publications/measuring-water-in-soil-capacitance
http://www.edaphic.com.au/soil-water-compendium/capacitance-or-frequency-domain/

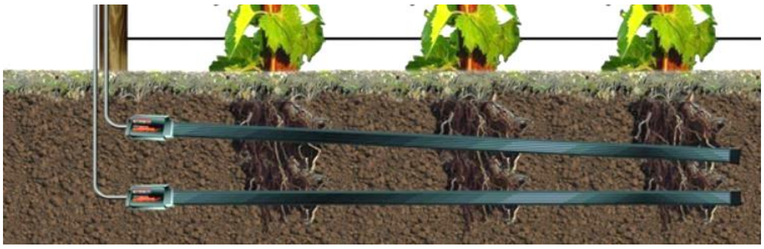
Time Domain Transmissometry (TDT)
This is similar to TDR however it measures the transmission of a plus along a looped or closed circuit rod. It measures the time taken for an electrical pulse. It would be much slower in wetter soils than drier soils. These are newer designed sensors compared to TDR or capacitance. In comparison, TDR probes reflect the pulse off the end of prongs. They are trickier to make than TDT as the reflected signal is lower.



Advantages	Disadvantages
Continuous monitoring of changes in soil moisture and temperature over time	Relatively expensive.
Data can be downloaded directly onto a laptop computer or, transmitted to a computer.	Soil disturbance during installation can cause unrepresentative conditions so needs to be installed early to allow time for the soil to settle.
Measuring soil water content across a larger volume gives a more representative reading than probe type sensors.	Can be noisy. Larger disturbance than TDR
Good accuracy	
Large sensing volume	
Inexpensive	

Sites:
http://www.edaphic.com.au/soil-water-compendium/time-domain-transmissometry-tdt/

Aquaflex



This uses a time delay transmission (**TDT**) technology to measure soil water content and temperature. The sensor is 3m long, and buried in a trench. It can be placed on an angle through the root zone or buried horizontally. Typically it runs from 50mm below the ground to 400mm which will cover the bulk of the rooting zone of pasture. An electrical pulse is sent through the sensor and the electric current changes shape and speed according to the amount of moisture present. An EnviroPro soil probe can be installed vertically to get moisture at different depths, having sensors located at every 10cm. Both 40cm and 80cm probes are available.

Sites:
https://www.scadafarm.com/solutions/scadafarm-soil-moisture
http://harvest.com/products/sensors/
http://www.acclima.com/poc7/prodlit/TDR-315L%20Data%20Sheet.pdf

For further information on soil moisture sensors, the Virginia Tech brochure by Sample et al. (2016) is very thorough.

Historical and current research

Currently, little research in New Zealand has advanced on this topic (soil moisture correlations with grass curing) since 2005. Promising results were identified with investigations into the relationships between the degree of curing and directly measured soil moisture, and the soil moisture indicators within the FWI System. Scion investigated the relationship between soil moisture content and the degree of curing during 1994 and 2004. It was hypothesised that the soil moisture and soil moisture indicators of the FWI system (DC & DMC) could be promising to estimate grassland curing. Correlations with the DC were studied because it represents the moisture content of the deeper soil and where the roots reside, and is therefore likely to have a greater influence on the curing percentage (as opposed to the upper soil layers represented by the DMC).

No direct soil moisture model was developed during this time, just trend lines (S-shaped curves) fitted through observation points for only a few sites (NIWA stations with soil moisture sensors) over only a couple of seasons (Baxter et al., 1999; NZ Fire Research, 2002a,b; Anderson & Pearce, 2003). There were two elements to this initial work: the first looking at relationships between curing values and measure soil moisture which, while showing strong correlations, varied between sites and seasons; and the other looking at rates of change of soil moisture vs rates of change in curing, which appeared much more promising, but still showed different relationships for different years.

In more recent years, there has been a move in research for hydrology and agriculture to using remote sensing for large scale soil moisture monitoring. This is based on measurement of reflected microwave radiation by satellite sensors, which is affected by the soil moisture (Ochsner et al., 2013).

Direct soil measurements and FWI relationships

The Fire Weather Index system (FWI) of the New Zealand Fire Danger Rating System (NZFDRS) consists of three moisture condes to track changes in the moisture content of forest fuels, and three fire behaviour indices to provide an indication of potential rate of spread, available fuel and fire intensity (Van Wagner, 1987).

Two of these moisture codes (DMC and DC) were hypothesised as useful indicators of the moisture content of soils layers, and research focused on these two codes (Baxter & Woodward, 1999; NZ Fire Research, 2002b). This is because weather factors, including temperature, relative humidity and rainfall, together with the day-length factors (and thus drying time), are already incorporated within both the DMC and DC (Van Wagner, 1978; Anon, 1993).

- The Duff Moisture Code (DMC) represents the moisture content of loosely compacted, decomposing organic material, and represents fuels down to a depth of 7 cm.
- The Drought Code (DC) represents the moisture content of deeper compact organic material, downed woody logs, and represents fuels down to a depth of 18 cm

In 1998, an initial relationship was found between the DC and degree of grass curing (Figure 10, $R^2 = 0.563$).

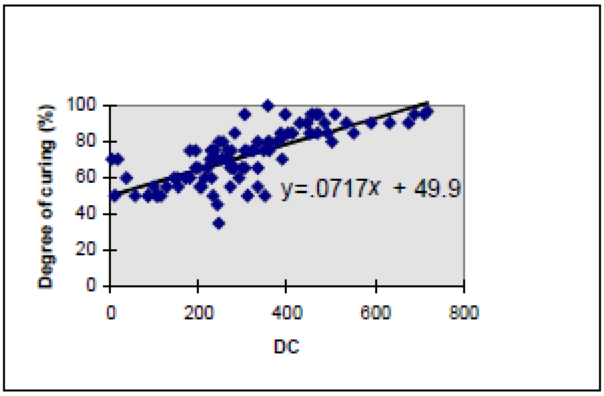


Figure 10. The relationship between the degree of curing and the DC.
Source: Baxter & Woodward, 1999.

Subsequently, investigations showed that the relationships between soil moisture, grassland curing and the DC and DMC were promising, but relatively weak statistically. The relationships were good during a particular season, but poor from season to season. Destructive soil moisture samples were also collected to check the accuracy of the weather station soil moisture sensors. The findings were:

- Soil moisture being measured by the weather stations accurately reflected the soil moisture conditions at the sampling sites (NZ Fire Research, 2002b).
- A strong relationship was found when soil moisture was tracked against the DC (NZ Fire Research, 2002b).

With more data from a range of sites and years, different relationships were found between the degree of curing and the DC (NZ Fire Research, 2002a). An "S" shaped curve was initially used to model the rate of curing over several seasons. A weak sigmoidal relationship between the degree of curing and the DC was identified. However, the relationship did not appear to be consistent between fire seasons. A number of the seasons monitored were unusually wet and may explain the scatter of the data. This made it difficult to establish a definitive trend or relationship for some fire seasons.

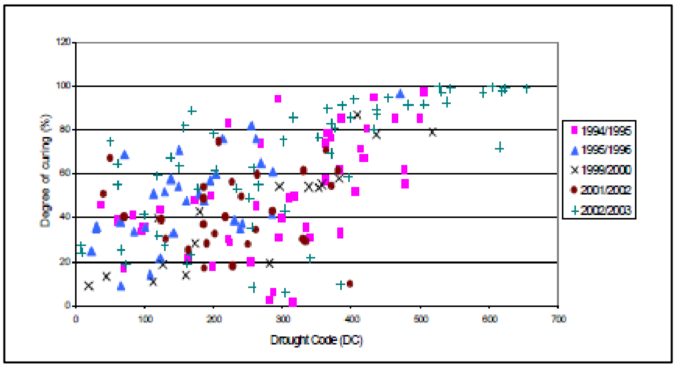


Figure 11. Degree of curing against Drought Code, plotted over five seasons.
Source: Anderson & Pearce, 2003.

The use of seasonal rates of change for the DC and DMC as a means of estimating the degree of curing was also investigated. Figure 12 below, represents the rate of change of the degree of curing against the rate of change of DMC and DC over the 1999/2000 summer season for one of the sample areas (Paeroa in the North Island) (Baxter & Woodward, 1999). It can be seen that the two curves do follow each other, and do so particularly closely at times. This method therefore also holds promise, with the potential to initiate rate of change relationships at the start of the season (in September or October) when curing values are low.

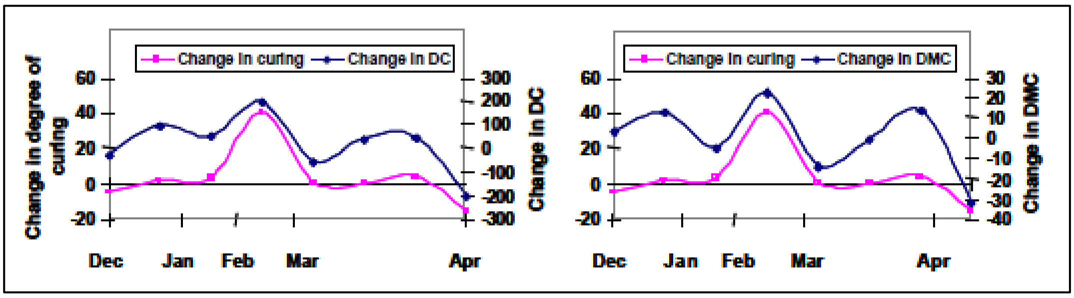


Figure 12. Rate of change in degree of curing versus change in the Drought Code (DC) (left), and the Duff Moisture Code (DMC) (right).

APPENDIX C. Pasture productivity background

Some work has also been done on use of pasture growth/productivity models for estimating curing. The suitability of pasture growth and senescence models (e.g., Donnelly et al., 1997; Moore et al., 1997) for predicting degree of curing in Australian and New Zealand grasslands have been assessed over the years (Garvey, 1997; Gill, 1999; Pearce & Anderson, 2003). Soil moisture is a key input into these, so again an enhanced network of soil moisture observations would aid this research and also enhance the potential to operationalize this approach.

AgResearch (Woodward) model

In 1998, a pasture quality model (developed by New Zealand's AgResearch) was assessed for suitability for estimating curing in grasslands (Baxter & Woodward, 1999). This model was developed for application in perennial grass/clover pastures, to predict the quantity of pasture production through the year, as well as the accumulation of dead material in summer pastures. Therefore, the model had the ability to calculate the amount of grass, cover and dead matter present in pastures, as well as the amount of live (green) material (Woodward et al., 1998; Woodward, 2001).

The pasture quality model required three daily weather parameters: mean daily temperature, daily rainfall (mm) and daily radiation receipt (MJ/sq m) (and/or number of sunshine hours per day).

Initial work by Baxter and Woodward attempted to calculate the degree of curing utilising the outputs from the pasture quality model, and results were encouraging. However, for this model to become operational, there are a number of improvements that need to be addressed, including the:

- Onset of seed head development (which is the first stage of the annual life/death process of grasses), was forced to a fixed date of 30 September. Work is required on determination of dates for first stem elongation (the initiation of the curing cycle) for different species.
- Water balance within the model also requires further validation and adaptation to different soil types. It is suggested that a more rigorous water table model to describe water movement in the root area (25 mm zone). Work on the water table will increase the ability of the model to estimate 'die-off' during years of extreme moisture stress. Currently the model allows movement of water between the shallow and deeper layers and thus the impact of drought may not be accurately modelled.
- Weather inputs required for the model are different to those currently used in the FWI subsystem component of the NZFDRS.
- Modification of the model to adequately reflect the growth and death processes in other grassland fuel complexes of different species (as opposed to ryegrass/clover dairy pastures). Other species may have slightly different physiological characteristics that affect curing.
- Incorporation of a "second growth" (resurgence of growth following a wet period late in the fire season). In the pasture quality model 'die-off' is modelled as a continuous process. Late season moisture may slow the rate of curing for perennial grasses (Cheney & Sullivan, 1997). Annual grasses are generally unable to green up once curing gets above 60%. There are times where new growth continues even though dead material is building up. This occurs until January 10; after this date, cool, rainy weather will act to slow curing, or continuing fine weather will 'maintain' high curing values.
- More work is also required in determining a solar radiation value based on a temperature/precipitation relationship

Dairy NZ models

There hasn't been any further development for some time using the pasture quality model, and researchers have moved onto Dairy pasture models. Most farm-focused pasture models have focused on green matter production and are relatively weak on dead matter build up (farmers try to avoid this). For example, the McCall pasture model (McCall & Bishop-Hurley, 2003), is a simplistic model but robust. The other widely used model for the diary/pasture industry is the Hurley Pasture model, and this has been further evolved into an AgPasture model, which is part of APSIM. Much like GRAZPLAN, the UK developed Hurley Model has several sub models to produce outputs. However, this is a large plant ecosystem model and the plant models are again not very strong on the dead matter side.

Other pasture models that were investigated and were unlikely to be suitable or dead ends include:

- The **BASGRA model,** which mainly focused on the winter stress and survival of plants. This is used regularly in northern Europe. It is not viable as an independent curing model because it is weak on dead matter build-up, but may have a useful feature with modelling the rates of senescence through frosts/snowfall during winter for places around the country that experience cold temperatures during the growing season.
- Pasturebase (Hanrahan et al., 2017),
- APSIM (Holzworth et al., 2014; Vogeler et al., 2016),
- STICS and CATIMO (Jégo et al., 2013; Jing et al., 2012)

GRAZPLAN

There are a number of decision support software for Agriculture in New Zealand and Australia. The GRAZPLAN project developed by CSIRO, is a series of computer models that form the basis of commercially available decision support tools (MetAccess, GrassGro, GrazFeed, AusFarm) (Donnelly et al., 1997). The tools were developed for farmers, farm advisers, agribusiness, banks and insurance companies. The most relevant of the models for curing is the GrassGro decision support tool.

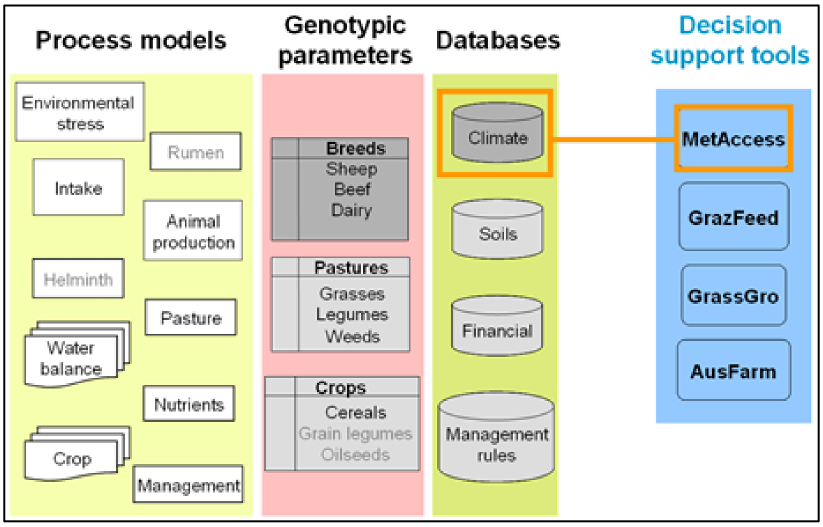


Figure 13. Scientific models in GrazPlan applications. Source: CSIRO. http://www.grazplan.csiro.au/?q=node/35

GrassGro™ is a discrete computer package developed for Microsoft Windows for the sheep and beef industry. It is a component of the GRAZPLAN decision support project for Australian grazing enterprises (Moore et al., 1997). GrassGro has been used to simulate grassland systems NSW, Victoria, Tasmania, South Australia, Western Australia, North America and Northern China. It is based on decades of field experiments.

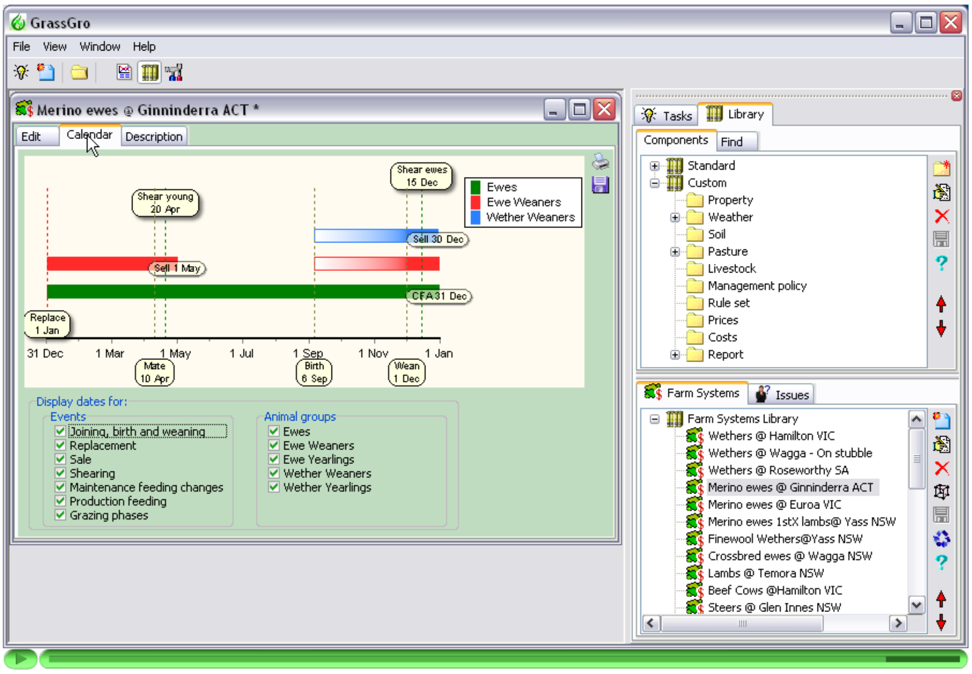
GrassGro™ combines the pasture growth module with a module (Grazfeed) for predicting the intake of animals (Moore, et al., 1997). The pasture growth module is quite general in structure but recognises four functional groups of pasture plants: annual and perennial species are distinguished, as are grasses and forbs (Moore et al., 1997). Shoot tissue is classified as live, senescing, standing dead, or litter, and also according to its dry matter digestibility, thus enabling integration with diet selection and feed intake models.

The inputs of historical daily weather drive the models of pasture growth and animal production. Day-to-day changes in water content of soil, pasture growth and decay and responses to grazing are simulated for a chosen enterprise. The user can look at the likely range of pasture and animal production over the next few months to answer any “what if” questions on short-term risks or opportunities.

To run the software, somewhat significant training and interpretation is required. The user:

- downloads weather data from a website
- describes the soil profile (physical properties required to determine its water holding capacity),

- Chooses from a list of temperate pasture species. The pasture can also be simulated as a grazed, un-grazed or mown paddock



Events
☑ Joining, birth and weaning
☑ Replacement
☑ Sale
☑ Shearing
☑ Maintenance feeding changes
☑ Production feeding
☑ Grazing phases

Animal groups
☑ Ewes
☑ Ewe Weaners
☑ Ewe Yearlings
☑ Wether Weaners
☑ Wether Yearlings

Figure 14. GrassGro interface

The inputs required to run the pasture model can include (Donnelly & Moore, 1997; Moore et al., 1997):

- Historical daily weather data (Rainfall, temperature, radiation, evaporation)
- Location, pasture species present
- Pasture species (temperature responses, water use, flowering control, maturation pattern, stress response (frost, water logging, drought), light capture, germination, dormancy)
- Soil description
- Soil data (texture, density, moisture, organic matter)
- Fertility level

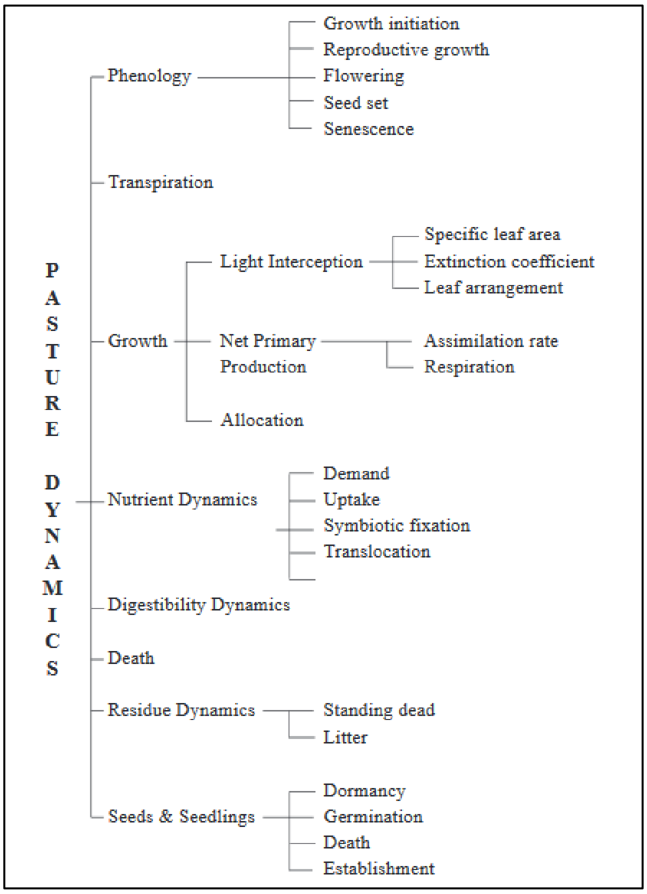


Figure 15. A framework of the processes of pasture growth for management modelling purposes. Source: Donnelly & Moore, 1997.

Daily models

Daily's (2012) research focussed on comparing three pasture models (APSIM, GrassGro™, SGS Pasture Model) and how they performed for several different grass types (introduced pasture and cereal grasses), as shown in the table below.

Table 7. Identity and growth habit details for target species used in the study.

Botanical Name	Common Name	Growth habit
Triticum aestivum L.	Wheat	Introduced cereal, synchronized annual phenology
Lolium rigidum Gaud.	Annual ryegrass	Introduced pasture, asynchronous annual phenology
Phalaris aquatica L.	Phalaris	Introduced naturalised perennial pasture
Austrodanthonia duttoniana (Cashmore) H.P. Linder	Wallaby grass	Native perennial pasture

These pasture models were not able to produce reliable curing estimates compared to the field assessments of curing, in part because the current state of knowledge on the senescence stage of leaf development has not been easy to incorporate into the models.

Daily (2012) then developed a basic "leaf curing model" for the same species grown in glasshouse conditions. The theory is that, curing can be determined by modelling the ratio of live/dead on each leaf. The study included calibration for each species in lab/field (Growing Degree Days (average temp over a day), Leaf turnover (development and death), leaf appearance, growth and death rates, curing (appearance, measurement, levy, destructive), soil depth, water hold capacity, bulk density, Weather. This model was based on the proportion of cured left material over time, but was not suitable for estimating curing in the field because it lacked responsiveness to plant leaf development and assumed irreversible curing. The model failed to react to rainfall green-up in perennials that were late in the curing phase. The greenhouse model didn't account for the possibility of significant rain late in the season. Daily's basic model appears to work in principle, but must be adjusted to the real life environment and New Zealand grassland species.

Daily et al. (Daily, 2012; Daily et al., 2013) then made improvements to the leaf curing model following validation, and created a Bayesian model that included the full range of leaf turnover characteristics calculated from glasshouse grown plants. This model predicted leaf biomass and percentage of dead material (curing percentage) over thermal time. Daily was able to validate this model with that in the field (levy rod) and suggested that this would provide a higher level of accuracy of grass curing prediction than the three pasture growth models that were investigated. The Bayesian model clearly demonstrated that the curing percentage could be predicted from thermal time, both under controlled environment glasshouse conditions and in the field, in four grasses with differing growth habits. The Bayesian model was superior to the basic curing model developed but still struggles to deal with "recovery"/second green up event after beginning senescence.

Studies undertaken by Daily will be useful to calibrate the senescence algorithms of plant growth models in agricultural decision support tools, which may then be applied to simulation studies including the assessment of grass curing for planning activities such as resource allocation, wildfire suppression, and execution of prescribed burning programs by fire management agencies (Daily et al., 2013).

APPENDIX D. Satellite technology background

Advances in research

It is noted that native and exotic grasslands comprise about half of all vegetative cover in New Zealand. Currently, grassland curing is largely monitored by observers on the ground making visual, which can be problematical in terms of subjectivity and the visitation frequency/extent of grasslands covered. Recent advancements in science now make it possible to take advantage of satellite remote sensing technologies with more accurate, regular curing assessments to provide full spatial coverage across the country (Figure 16). If undertaking this approach, it is recommended to leverage or build on the solid base of historical research and collaboration by Scion, Australia's CSIRO and Bureau of Meteorology (BoM).

Previous research to develop methods for assessing grassland curing was conducted within the Bushfire CRC (led from NZ by Stuart Anderson from Scion), involving the Australian Bureau of Meteorology and CSIRO Land & Water. This resulted in a remote sensing method based around relationships between grass curing and satellite-derived NDVI.

In 2009-10, MODerate resolution Imaging Spectroradiometer (MODIS) satellite data was investigated for determining curing in Australia and New Zealand (Newnham et al., 2010; Clifford, 2011). The trial was very promising, and become the basis of the Victorian and NSW grass curing methods employed today. Historical ground-based curing observations were collected during 2005 to 2012 and tested against satellite-derived maps. These maps were created on an 8-day composite basis, usually provided on fortnightly intervals. Several fire agencies from NSW, Victoria and New Zealand were involved to validate the performance of the algorithms. Four equations were evaluated for New Zealand (and SE Australia) during the first pilot trail conducted in 2009/10, from which two were identified to work best for New Zealand. These two equations were further trialled in 2010/11, but no definitive conclusion could be drawn from the results and further investigation was recommended.

The use of remote sensing data for assessing vegetative fire risk (i.e. including forestry and other land cover quite apart from grasslands) has advanced markedly in recent years; a global review of this, and steps towards achieving operational systems able to deliver prompt information of practical utility, has been published by Yebra et al. (2013) and an operational system developed to cover Victoria (Australia), has been described by Martin et al. (2013).

In 2015, Scion utilised the expertise of CSIRO and the Bureau of Meteorology (BoM) to further investigate evaluation and improvements to the previous map algorithms for New Zealand (Newnham et. al., 2015). This resulted in a number of recommendations for future mapping of grassland curing in New Zealand. The best performing models were the Bushfire CRC model B and Map Victoria model, but these require further assessment for accuracy with independent data. Completing processing of MODIS surface reflectance time series and testing of different compositing methods were further recommendations from this work. Work on compiling the historic time series was initiated with NIWA, but was never completed due to resourcing issues.

In Australia, satellites are routinely used to monitor the reflective properties of grasses. In Victoria, state-wide maps of curing are generally produced weekly using satellite and field information to show how dry grasslands are across Australia (Figure 17) these are processed by BoM and displayed on public websites. Today, Victoria has an operational online system that can be accessed by web browsers across various platforms, and comprises a web portal, a cloud-based database and application server, and a geo-processing service.

These maps are currently based on MODerate resolution Imaging Spectroradiometer (MODIS) satellite data. MapVictoria was developed during 2012-2013, which looked at MODIS satellite data and ground observations during 2005 and 2013 (Newnham et al., 2010).To improve accuracies even further, an integrated system called the Victorian Improved Satellite Curing Algorithm (VISCA) has been developed. It combines near-real-time satellite data with weekly observations of curing from the ground into an automated online system (Alexander et al., 2014; Martin et al., 2015). Access to near real-time satellite data has also improved the temporal accuracy of curing (Wright et al., 2015). Weekly curing observations by up to 450 observers were entered in the system, validated by operational personnel and used by VISCA to adjust the MapVictoria satellite observations (Wright et al., 2016).

The Terra satellite with MODIS sensor makes passes over Australia every 1-2 days. This satellite produces a pixel curing value for every 500m x 500m of land. The reasons for relying on human observers to collect curing data is because a state cannot rely solely on satellite data. Mostly due to issues with cloud cover or technical issues around the satellite and receiver. In Australia, there are a few different methods are being used operationally today and discussed in the main body of the report (based on correspondence with CFA staff).

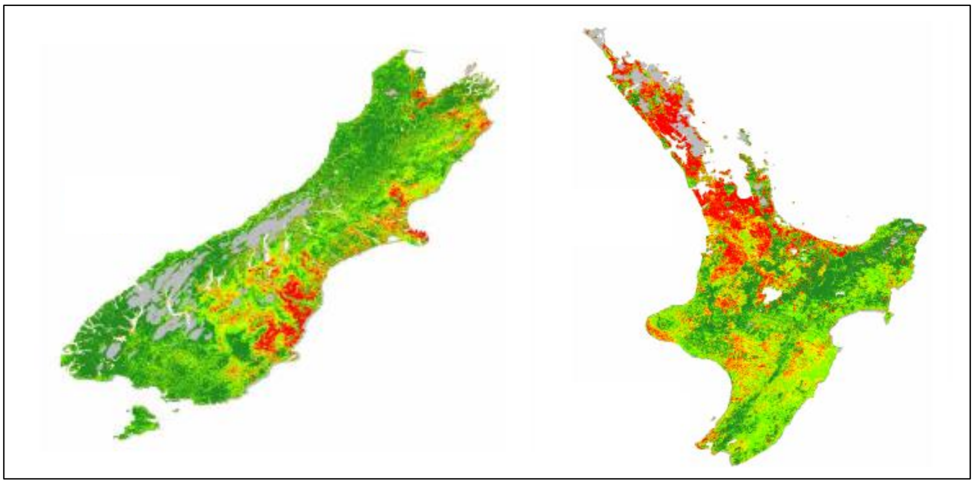


Figure 16. Example grassland curing maps from a piolet trial using Bushfire CRC model C. Source: Clifford et al., 2011

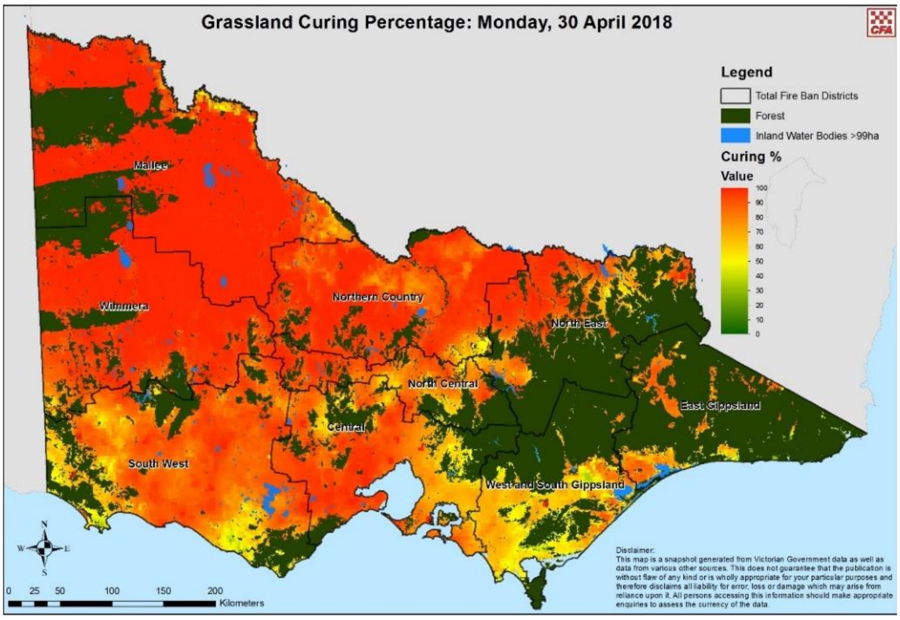


Figure 17. Example grassland curing map. Source: http://cfaonline.cfa.vic.gov.au/mycfa/Show?pageId=colGrasslandCuringMap

Normalized Difference Vegetation Index (NDVI)

Satellite-based remote sensing involves creating images using sensors sensitive to parts of the electromagnetic spectrum. Satellite sensors monitor reflected light including visible bands that isolate red, blue or green, and non-visible bands in the near-infrared, thermal infrared or microwave regions.

In terms of grassland curing, satellite remote sensing systems uses the reflective properties at different wavelengths to calculate an index. The unique spectral signature of vegetation enables it to distinguish between live and dead components, and from other objects. Healthy vegetation will reflect green (peak) and absorb blue and red light energy (decrease) in the visible light region. In the near infrared (NIR) region, the reflectance is much higher than that in the visible band due to the cellular structure in the leaves. A plant with more chlorophyll will reflect more NIR energy than an unhealthy plant. Therefore vegetation can be identified by high NIR and low visible reflectance. Vegetation indices (such as NDVI) are the most widely used remote sensing tool.

The conventional remotely-sensed measure of vegetative land cover, the Normalized Difference Vegetation Index (NDVI), makes use of the grassland reflectivity in part of the spectrum outside of the visual range, specifically in the near infra-red (NIR), where the reflectivity of grass/vegetation enlarges markedly. This increase is often referred to as being the ‘Red Edge’, occurring in a wavelength range starting at about 0.69 μm and continuing through to 0.80 μm, where the slope levels off; the Red Edge marks the transition between chlorophyll absorption and cellulose reflectance.

The point of mentioning this here is that there are satellite sensors, either already in orbit or else due for launch in the next four or five years, that have been designed to study the Red Edge in detail. Similarly, there are satellite sensors given spectral bands specific for studies of chlorophyll in living plant material. In view of this it seems clear that although initial stages of a grassland curing project would concentrate on the conventional NDVI (i.e. making use of only a Red and a NIR band), and on alternative algorithms based on the NDVI, there are other satellite data – other wavelength bands – that might be considered for future utilisation, including in the SWIR. Further, it is noted that some recently-launched satellite sensors are returning imagery for visible wavelengths where chlorophyll absorption dominates, providing another channel through which useful GCI algorithms might be feasible.

To determine the NDVI, the satellite sensor must collect imagery at around 0.67 μm (Red), and 0.86 μm (NIR). Whilst most VNIR sensors do collect light in bands around those wavelengths, it is also possible that the spectral bands may be too broad to be useful if one needs to calculate valid NDVI values. That is, the spectral resolution may be sub-optimal. As will be seen later, this criterion leads to certain satellites/ sensors being excluded.

The next consideration is the temporal resolution: how frequently are NDVI evaluations needed? A telecon with Scion staff indicated that once per week may be adequate, although a more rapid tempo would be desirable. Given that clouds (in particular) interfere with imagery collection on many satellite passes over New Zealand, clear images might be anticipated at least once per week, so long as suitable passes occur every couple of days. It is this that then informs the spatial resolution limitation.

From Low Earth Orbit (LEO), and assuming basic orbital and Earth geometry to obtain adequate temporal coverage from a single satellite limits the spatial resolution to around 250 or 300 metres. On the other hand, a constellation of four satellites in the same orbit (but spaced in position), each having ground sampling distances (GSDs) of 250-300 metres, would deliver more-frequent complete coverage of New Zealand and, importantly, differing view angles as they pass above or near New Zealand.

Candidate satellites and sensors

Over the past five years there has been a substantial increase in the number of satellites potentially-useful from the perspective of acquiring imagery from which grassland curing might be determined. It was formerly the case that the most-useful satellites were operated by the US Government (through NASA, NOAA and the USGS), but now there are ESA and Japanese orbiters from which imagery might be acquired, plus many other nations operating satellites with varying levels of data accessibility. There are also numerous commercial satellite companies, although those mainly collect simple ‘true colour’ imagery rather than the NIR (and perhaps SWIR) data required for vegetative index (VI) measurements.

All satellites and sensors which might be of use for assessments of grass curing in New Zealand using some form of algorithm based on the conventional NDVI (i.e. using comparative reflectivities in the red and near-infrared parts of the spectrum) were considered. This involved a total of 49 presently-orbiting satellites, if one counts Planet Lab’s Dove constellation (over 180 cubesats), RapidEye five-satellite constellation, and SkySat twelve-satellite constellation, as just three units (rather than 200 distinct orbiters, all operated by Planet). In general, these satellites are in (low-Earth) polar orbits and pass over territory below at a consistent local time-of-day.

From those 49, many satellites can be dropped for various reasons (e.g. the commercial satellites have swaths that are too narrow to be able to render useful imagery on an individual basis, and in any case the data would need to be bought, whereas there are satellites operated by various governmental organisations for which free data access is feasible). Of course, imagery with small GSDs can be degraded/averaged over many pixels, but high spatial resolution generally means narrow swath or imaged areas, and the need here is for wide area coverage and frequent revisits (once a week or better).

Table 8 lists sixteen satellites (pared down from the original 49) that were selected for more detailed evaluation; for some rows in that table there are multiple satellites entered because of the same instrument being employed (e.g. MODIS on Terra and Aqua), whilst other rows pertain to different sensors on the same satellite (e.g. MODIS, ASTER and MISR on Terra).

The boxes highlighted with a pink background in Table 8 are indicative of reasons to exclude particular satellites/sensors from further consideration. The boxes highlighted in light blue are those indicating reasons for being cautious regarding a sensor, though perhaps not rejecting it outright.

The third column in Table 8 involves the spectral bandwidth used for the relevant (from the perspective of NDVI calculation) Red and NIR bands in each sensor. Generally, those bandwidths are acceptable, but in the case of the AVHRR/3 sensor they are quite large; preferred would be bandwidths of around 60 nm centred on about 670 nm for the Red, and similarly 60 nm centred on about 860 nm for the NIR. The GSD for AVHRR/3 is also large (as indicated in the fourth column of Table 8). Overall it seems clear that the satellites flying the AVHRR/3 instrument are not suitable sources of imagery for the project in hand. Other GSD values in the fourth column that are large include those for bands 3 and upwards on MODIS (bands 1 and 2 – Red and NIR – have GSD=250 metres), and the GSD=500 metres for the SLSTR instrument on Sentinel-3A and 3B. It is desirable that the GSD be smaller than this. The other instruments have GSDs generally 300 metres or less; the Red and NIR sensors of the VIIRS instrument (bottom two rows in Table 8) have GSD=375 metres, which could be acceptable from the perspective of the present project.

The swath widths shown in the fifth column of Table 8 and the revisit times in the sixth are interrelated. The global revisit time in days can be estimated by dividing the circumference of the equator (40,000 km) by the swath width, and then by the number of orbits per day. Note that the revisit times will be less (i.e. more frequent) for New Zealand due to our latitude/distance from the equator.

The revisit intervals in the sixth column are per satellite. That is obvious for Landsat-7 and -8, but because they follow the same orbit (and are separated by 180 degrees in their positions) their combined revisit time is reduced to eight days. This might be marginally acceptable from the perspective of measuring grass curing, if clear skies could be guaranteed, which is infeasible. The overall revisit time for the Landsat-7/Landsat-8 pair with clear skies would therefore be expected to be more than a fortnight, and to be seasonally-varying. In some parts of New Zealand it may well be that cloud coverage is more likely across the months of interest (late summer), whereas elsewhere it is perhaps the case that the skies are clearer in late summer. Regardless, it appears that the long revisit interval from the Landsat orbiters implies that they would not be of utility regarding the collection of NDVI values with the necessary tempo (weekly, or better).

The long revisit time (48 days) for the ASTER instrument on Terra means that it is coloured pink and excluded from further consideration. In any case it is not to be expected that either the Terra or Aqua satellites will continue in operation for more than a handful of years into the future; they were launched in 1999 and 2002 respectively. The prospective longevity of each satellite is shown in the final column of Table 8.

The JAXA satellite GCOM-C1 would appear to meet the requirements here: appropriate sensors for NDVI, GSD 250 metres, and a global revisit time of once every two days. In addition, GCOM-C1 (launched in December 2017) is the first in a series of similar satellites, so that within a few years it is to be anticipated that more frequent coverage will be available. In any case, if GCOM-C1 alone scans New Zealand once every two days, we may expect cloudless imagery for much of the country on a weekly basis at worst.

The Sentinel-2A and 2B sensors each render revisit intervals of ten days, but in combination this reduces to five days. Two further Sentinel-2 satellites are scheduled for launch within a few years, and then the overall revisit time will reduce to 2.5 days (in fact, two days at New Zealand's latitude), and so weekly cloud-free imagery may be anticipated. Note also the comparatively high spatial resolution (GSD 10 or 20 metres). Sentinel-3A and 3B can potentially deliver New Zealand imagery with a frequency of once every two days or better. The OLCI sensor has an acceptable GSD (300 metres), and in combination with that the GSD=500 metres imagery from the SLSTR sensor will also be useful.

The next row in Table 8 pertains to ESA's Proba-V satellite. Whilst this experimental orbiter was designed specifically for studies of vegetative land cover, it is expected to have its mission terminated later this year. Reasons for excluding those satellites employing the AVHRR/3 instrumentation have already been explained above.

The lowermost two rows in Table 8 refer to the predominantly-meteorological satellites Suomi-NPP and NOAA-20, both of which carry VIIRS instruments. Note also that these two will be joined within some years by identical satellites, presumably to be named NOAA-21 and NOAA-22 once they are deployed. This constellation is termed the Joint Polar Satellite System or JPSS, 'Joint' because the satellites have been developed by NASA, are operated by NOAA, and the Department of Defence was originally involved in the overall project. The relevant bands for NDVI evaluation (Red and NIR) have GSD=375 metres, which is acceptable for present purposes, although a smaller value/better spatial resolution might be preferred. What this eventual constellation of four (and possibly more) satellites using VIIRS instruments has much in its favour is a revisit time that is brief, with New Zealand being scanned several times a day by the group. Note also that VIIRS has bands (with GSD=750 metres) that cover the vegetative 'Red Edge', and another band of known utility in measurements of vegetative cover in the short-wave infra-red (SWIR) (with GSD=375 metres).

Table 8. Comparison of satellites and sensors from the perspective of NDVI measurement capability. Pink boxes, are reasons to exclude particular satellites/sensors from consideration. The boxes highlighted in light blue are highlighting causation, but not rejecting it outright. The column GSD refers to the spectral bandwidth used for the relevant Red and NIR bands in each sensor for NDVI calculation.

Satellite Name	Instrument	Spectral Bands (for NDVI)?	GSD (m)	Swath Width (km)	Global Revisit Time (days)	Longevity (from present)
Landsat-7	ETM+	Yes	30	185	16	To be replaced by Landsat-9 from 2020
Landsat-8	OLI	Yes	30	185	16	Decade+
Terra & Aqua	MODIS	Yes	250/500/1,000	2,330	1	Few years
Terra	ASTER	Yes	15/30	60	48	Few years
Terra	MISR	Yes	275	360	9	Few years
GCOM-C1 Shikisai	SGLI	Yes	250	1,150/1,400	2	Decade+
Sentinel-2A & 2B	MSI	Yes	10/20	290	10	Decade+
Sentinel-3A & 3B	OLCI	Yes	300	1,270	2	Decade+
Sentinel-3A & 3B	SLSTR	Yes	500	1,420	2	Decade+
Proba-V	VGT-P	Yes	100/360	2,250	2	Planned end of mission later in 2018
NOAA-18 & NOAA-19	AVHRR/3	Sub-optimal (quite broad)	1,100	2,900	1	Few years
MetOp-A	AVHRR/3	Sub-optimal (quite broad)	1,100	2,900	1	To be replaced by MetOp-C late in 2018
MetOp-B	AVHRR/3	Sub-optimal (quite broad)	1,100	2,900	1	5-8 years (then to be replaced)
Suomi-NPP	VIIRS	Yes	375/750	3,000	1	Decade+
NOAA-20	VIIRS	Yes	375/750	3,000	1	Decade+

Remote sensing - Considerations, Assumptions and limitations

Viewing angles as the satellite passes NZ

The telecon with Scion staff (23 May) indicated that the concern here is shadowing or obscuration by mountains and hills. For a ground position at the edge of a swath of width 1,250 km the elevation angle of a satellite in LEO at altitude 800 km is close to 45 degrees. That is, the satellite appears to be midway between the horizon and the zenith. This is the 'worst case' for such a swath; for other positions in the swath the satellite passes closer to the zenith (larger elevation angle). Note that for a pushbroom sensor (i.e. not like a camera taking an instantaneous view of a 2D scene below) the only *viewing* angle involved is that transverse to the satellite's motion (i.e. 'sideways').

The paths taken by satellites with wide swaths as discussed above are generally such that on one day there are consecutive passes to the east and the west of New Zealand which overlap in terms of ground coverage, New Zealand being near the periphery of the swath in both passes, but the next day there is one pass which crosses New Zealand quite centrally. This is the case with Terra/MODIS, the data from which was used previously by Scion in grass curing assessments.

The existence of a constellation of (say) four satellites in identical orbits leads to multiple passes each day with one or two crossing with New Zealand close to nadir (i.e. near the centre of the swath, limiting any possibility of shadowing by mountains etc.).

Issues: cloud cover, snow, mountains (obstacles), image processing?

Obviously enough there is nothing that can be done about cloud cover from the perspective of imagery in the VNIR. The influence of cloud was already mentioned above, where it was assumed that to obtain weekly clear imagery of New Zealand it would be necessary to have satellite passes at least once every two days, to accommodate perhaps two-thirds of all passes being affected by clouds. Snow cover does not seem to be a problem, unless grass curing in hill country needs to be assessed across the winter months, which seems unlikely from a fire hazard perspective.

The influence of mountains and other obstacles is *not* limited to considerations of the viewing angle, which was discussed just above. Another angular consideration is the solar illumination direction. Polar-orbiting satellites generally cross the territory below at a consistent local (solar) time of day, most often either late morning (around 10:30) or early afternoon (around 13:30), so that the solar illumination direction varies only slowly, with the season. The direction of the Sun alters as it moves north and south across the seasons. This has scattering angle and shadowing effects at the ground, so that it is necessary for some applications to calculate the solar azimuth and zenith/elevation angle; for wide swaths it might be necessary to do this on a pixel-by-pixel basis, rather than just for the centre of a composite image built up from the transverse strips across the swath as the satellite progresses in its orbit.

Another aspect of solar illumination angle is the possibility (indeed certainty) that within an image there are shadows cast by mountains and other obscurations. Within those shadowed regions the ground/grass will be illuminated only by scattered light from the sky, and not direct sunlight. The distribution of intensities as a function of wavelength is different between scattered sunlight from the sky/atmosphere, and direct sunlight, so that the NDVI will be affected. This effect will be greater during the winter, when the Sun is further north and lower in the sky (casting longer shadows, and also traversing longer path lengths through the atmosphere), but reduced in the summer when the Sun is higher in the sky; and this is the time of year when grass wildfires are more likely, and grassland curing needs measuring. Nevertheless, this shadowing effect will require investigation. Note that it may be necessary, in this regard, to employ imagery of a higher spatial resolution than otherwise used in grass curing assessments. That is, the data with 250/300 metre pixels may be too coarse to allow shadowing effects to be examined, and so some higher-resolution imagery may be needed (e.g. Landsat data with 30-metre pixels, or Sentinel-2 imagery with 10/20-metre pixels).

This provides a segue into the last point under this heading. To obtain the best possible outcomes from the satellite data, a variety of image processing techniques will need to be applied. Calculating a NDVI image from raw Red and NIR images is straightforward, but experience indicates that (to arrive at a better understanding of what the result implies) there are various adjustments that will need to be made. One of these is linked to the influence of the changing solar illumination from day-to-day and week-to-week, but also the variation in the solar illumination angle across a single image, especially when wide swaths are used, as here. An exploration of this will require an experimental programme. It is also noted here that a Japanese polar-orbiting satellite (GCOM-C1) launched at the end of 2017 carries a sensor with two polarisation channels, operating at the Red and NIR wavelengths involved in NDVI evaluations; polarisation information will enable an improved assessment of how the scattering angles affect the reflected intensities of light at the wavelengths used in the NDVI algorithm.

Costs

As aforementioned, the satellites that appear in Table 1 have been culled from a larger contingent of 49 satellites, which included essentially all VNIR imaging satellites in LEO. All those satellites/sensors in the reduced list in Table 1 are operated by governmental organisations to which prompt and free data access should be feasible. This is presently the case for the U.S. satellites, and CSST staff have extensive experience of accessing data from distribution systems operated by NASA, NOAA the USGS and the ESA Sentinel series.

It should be mentioned here that the satellites in Table 1 were not selected simply because of being free sources of data. The necessary wide swaths are generally not available from commercial sources, because their business involves high-resolution imagery in narrow swaths.

Longevity of equipment/sensors

This longevity factor has been explicitly considered in the analysis of the satellites short-listed in Table 1. For example, ESA's experimental orbiter Proba-V (the V stands for Vegetation) would appear to be ideal for present purposes – supposing that imagery of New Zealand is collected and downloaded – but that satellite has now exceeded its planned lifetime and is expected to be withdrawn from service later in 2018.

The satellites in Table 1 selected for possible utilisation (see section 2) all have anticipated lifetimes in excess of ten years; they are also members of constellations with likely additional satellite launches within the next few years.

Flexibility – data fusion with other methods (i.e. ground visual observations, soil moisture sensors)

There is nothing to prohibit or limit the fusion of information derived from satellite imagery with data acquired in other ways. CSST would be able to make satellite-derived analyses available in any desired file format.

Regarding soil moisture information, it is noted here that the brief for this proposal was limited to grass curing assessments using satellite imagery and algorithms based on the conventional NDVI (and therefore the Red and NIR wavelengths). It is certainly true that other spectral bands are of utility in this regard (for example in the SWIR, at 1.6 μm), and that the Bushfire CRC and Scion have previously explored the use of MODIS SWIR bands in an adjusted NDVI algorithm; this matter (using other bands in the VNIR/SWIR) deserves further investigation. It is noted that there are satellites in orbit and/or planned which have sensors employing spectral bands across the visible region of the spectrum specifically selected for their sensitivity to chlorophyll absorption (i.e. reduced reflectivity). In addition, however, various satellites are now being operated in programmes aimed at measuring soil moisture from orbit, using both passive (microwave emission) and active (radar at various frequencies) sensors. Since soil moisture is fundamental to both the growth of plants and their dying/drying/curing (and consequent role as fuel for wildfires), it seems appropriate that further study of how such satellite data might be used in New Zealand in the future should be considered. There are various ways in which radar-equipped satellites might be of utility in various regards, not least because they are unaffected by cloud cover.