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Environment
Manatū Mō Te Taiao

Ministry for Primary Industries
Manatū Ahu Matua

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Overseer whole-model review

Assessment of the model approach

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Executive summary

The degradation of freshwater is a key environmental challenge of our time and nutrient enrichment from agriculture is a major contributor. Nutrient losses from farms respond to various factors, including management and climate. Measuring nutrient losses is challenging and cannot capture the entire range of possible conditions that might occur. Models, therefore, present an opportunity to estimate these losses. From a Māori perspective, the priority is protecting Papatūānuku (our natural resources) and models have the potential to support kaitiaki in upholding the mana and mauri of Papatūānuku. Overseer is one such model that aims to estimate farm-scale nutrient flows. We (the Science Advisory Panel) have reviewed Overseer to assess whether the current modelling approach gives us confidence that Overseer can predict what impact changes in farm management may have on losses of nutrients into water. We assessed Overseer in the context of the key nutrients that are contributing to freshwater degradation. We recognise the important role phosphorus plays in this context, although due to the nature of Overseer's documentation we were not able to review it as thoroughly as nitrogen.

This review was commissioned by the Ministry for Primary Industries and the Ministry for the Environment in response to the Parliamentary Commissioner for the Environment's (PCE) 2018 report and in the context of the Essential Freshwater programme and its goals for freshwater quality. The PCE report was in part a response to Overseer's increasingly important role in freshwater regulation, despite being "a black box". This review draws on mātauranga Māori as well as modelling, agricultural sciences, and nutrient dynamics. The review does not consider the user-interface, greenhouse gas modelling, or any other aspect of the suite of tools under the Overseer brand, other than nutrient modelling. Furthermore, the review did not examine whether Overseer could be used as a social tool to encourage farmers to adopt nutrient management strategies, nor whether it would improve the credibility of recommendations from rural advisers.

Overseer Ltd and AgResearch provided us with information about the model, including information not in the public domain, protected as Overseer Ltd's intellectual property. We had the opportunity to discuss this modelling information with staff from both organisations. We also heard from several users of the model, and Waikato Regional Council and Environment Canterbury staff. We thank all of those who gave their time and expertise for their open, constructive approach to the review and their professionalism.

Overseer's approach

Overseer originated in the 1980s providing long term phosphorus and lime recommendations and has been under development for many years with incremental modifications over time. Overseer uses actual or predicted production information (e.g., animal products, crop yield) defined by the user to back-calculate plant growth, rather than using climate inputs along with plant, soil, and landscape characteristics, combined with management, to predict plant growth. Having back-calculated plant growth, the model then uses this to define soil water and nutrient demand. These are used in calculations of water and nutrient dynamics. Thus, plant growth is not directly related to weather, available soil water, or nutrients. Overseer relies on users to describe animal or crop performance in a realistic way, including the amount of fertiliser applied to achieve these performance outcomes.

Overseer's reliance on user-defined agricultural production is a benefit to the usability of the tool because it uses information readily available to farmers. Farmers and advisors are able to estimate nutrient loss from farm management scenarios with limited training in model use. Overseer relies on users to self-check that scenarios are realistic, which removes the need for the model to predict output variables that users likely already know (e.g., their production for past years).

Overseer aims to provide a quantitative description of farm nutrient dynamics. Since the emphasis of this review is on freshwater quality, the focus is on nitrogen and phosphorus. It appears that Overseer is primarily calibrated towards estimating nitrate leaching loss in soil drainage water, but ecosystems respond to total nutrient losses from farm, not a particular form of nitrogen. This is particularly important in landscapes with soils that are classed as being imperfectly to poorly drained, which make up over 50% of Aotearoa New Zealand's productive land.

Overseer's structure and data

Overseer can use datasets automatically (e.g., climate and soil data). The automatic use of datasets improves usability and reduces the burden on the user to source data that may not otherwise be easily available (e.g., soil characteristics). Overseer uses a long-term average climate data file generated by NIWA for 1981 to 2010. It runs on a monthly timestep, except for the hydrology model, which uses a

daily timestep. Results for drainage are then aggregated up to monthly values for use in further calculations.

This structure rests on several assumptions.

- Overseer assumes actual and reasonable inputs; it relies on users to self-check that farm systems are realistic. Although a reasonable approach when using historical data to establish nutrient loss for a past farm system, it limits the model's usability for 'what if' scenarios, when outputs are estimated to varying degrees of accuracy.
- Overseer assumes good management practices.
- Overseer assumes steady state conditions and that the farm system is in quasi-equilibrium; farm system inputs (e.g., fertiliser, irrigation, feed) and site characteristics are assumed to be in equilibrium with farm production.

Overseer produces long-term annual averages, with users defining average management, inputs, and production, to give an estimate of what the long-term average nutrient losses would be. Overseer does not, and does not purport to, calculate a farm's nutrient loss for a particular year.

Overseer assumes that, over the long-term (e.g. 30 years) the results from the model with average climate and management inputs will be equivalent to those that would be obtained by using actual inputs and then averaging the results. In general, this is only true for linear systems. Furthermore, by ignoring actual climate variation, the corresponding variable characteristics of nutrient flows in response to climate are not captured in model outputs. For example, periods of high (but not uncommon) rainfall may lead to significant runoff, deep drainage, and losses of nutrients, and such events will not be captured when only using average rainfall. As well as these concerns, determining average rainfall patterns is difficult since these must capture both the frequency and amounts of rain, and these are highly variable.

A feature of Overseer is that it does not necessarily balance mass. Therefore, the amount of nitrogen initially in the system plus the amount added may not equal the amount remaining at the end of the simulation less the amount removed and lost. Mass balance is a core requirement of any model that aims to track water and nutrient dynamics reliably. If mass is not balanced, the user cannot have confidence in the model's outputs, particularly nutrient losses from the system.

Overseer represents the soil as a homogeneous profile and does not capture variation in water and nutrient distribution through depth. Overseer uses different soil depths for different processes and does not model how those processes are related to each other. A more rigorous treatment could be designed using a multi-layer model for all processes. This would impose no greater data requirements on the user but would allow for a more accurate description of water and nutrient dynamics, and nutrient loss estimates.

The use of average climate data, the homogeneous soil profiles, and the omission of ammoniacal nitrogen and soil organic matter dynamics mean that Overseer's predictions do not account for potentially significant components of nutrient losses. In addition, Overseer does not and was never intended to model episodic events such as intermittent heavy rain or dry spells. This is a significant weakness, as episodic events are critical drivers of nutrient losses and farm plans to manage nutrient loss should factor such events into mitigation strategies.

Testing Overseer against experimental data is problematic due to its use of average climate

Until now, most testing of Overseer has focused on comparison with experimental data. There are reports showing favourable comparisons between experimental data and Overseer estimates. However, when comparing models with experimental data, it is important to ensure that model inputs reflect those applied during the experiment. This is not possible with the model using 30-year long-term average climate data. The comparison of long-term average nitrate leaching calculated based on long-term average climate data, with nitrate leaching measured over a short-term (maximum two-three year) experiment influenced by real climate, may not be helpful, for example, if the experiment was conducted during a drought. There are enormous challenges in testing complex biophysical models with experimental data, and Overseer's structure makes testing against experimental data difficult. Therefore, there should be a strong focus on investigating internal model structure to ensure it represents the biophysical processes adequately – which we have done.

Relative and absolute nitrate loss estimates are unlikely to be reliable

Based on our discussions with regional councils, they considered that, for their application, the accurate prediction of absolute nitrate losses is not essential because regulations rely on relative comparisons of nutrient loss estimates for different management scenarios. However, model accuracy is required to provide confidence in either relative or absolute values. Using relative values will only cancel out model biases in the rare scenario that biases are equal and in the same direction in both management scenarios. However, if the model accuracy is different for the two scenarios then the relative value is not guaranteed to be any more reliable than the absolute value. Overseer is, therefore, unlikely to be a reliable tool for predicting either relative or absolute nutrient loss estimates.

Engagement with Māori

Throughout model development, there was no engagement with Māori. This is symptomatic of wider systemic issues in Aotearoa New Zealand's science system. We understand that Overseer Ltd has more recently begun engaging with Māori by supporting Māori agribusinesses to use the tool. However, for a model to be used in regulation in Aotearoa New Zealand, its developers must engage with and learn from Māori throughout the process.

From a Māori perspective, the reduction of environmental impact down to just one or two contaminants is problematic. The use of models – with their necessarily reductionist limitations – should also be done in the context of a more holistic analysis of te taiao. Models are designed to model certain environmental and landscape conditions, but all will have some landscapes that they are not suited to model. The desire to simplify the natural world for ease of administration by using models and ignoring the inconvenient complexities of agricultural and environmental context should be strongly resisted.

Structural concerns outweigh sub-model coherences

Although Overseer's user interface and the use of actual production metrics make it a user-friendly model, it was not originally designed for its current use of accurately estimating nutrient losses. Therefore, its structure does not adequately represent the complex system dynamics underpinning nutrient loss and this limits the confidence we can have in its outputs. Our core concerns are that Overseer:

- Is a steady state model attempting to simulate a dynamic, continually varying system;
- Uses monthly time-steps;
- Uses average climate data and, therefore, cannot model episodic events, or capture responses to climate variation;
- Does not balance mass;
- Does not account for variation in water and nutrient distribution in the soil profile;
- Does not adequately accommodate deep-rooting plants;
- Focuses on nitrate and omits ammoniacal nitrogen and organic matter dynamics; and
- Lacks consideration of surface water and nutrient transport, as well as critical landscape factors.

As a result of these concerns, we do not have confidence that Overseer's modelled outputs tell us whether changes in farm management reduce or increase the losses of nutrients, or what the magnitude or error of these losses might be. Although some of Overseer's components, such as the animal metabolisable energy sub-model, appear sound, these coherences are outweighed by overarching structural problems. We, therefore, consider that Overseer's structure is not adequate to provide more than a coarse understanding of a farm's nutrient losses (except for surface flows since these are not included in the model). It cannot reliably estimate how changes in farm management would affect those losses.

Future efforts to help understand, quantify, and reduce these losses may include development of biophysical models, possibly in conjunction with simple decision support tools. There may be aspects of the Overseer model, such as its user interface, that can contribute to developing these tools. Decisions on the way forward will no doubt take into account many factors but should be driven by what will lead to the best outcomes for freshwater quality in Aotearoa New Zealand.

Whakarāpopoto matua

He wero taiao matua te tāhawahawatanga o te waimāori o tō tātou wā, otirā ko te kaitāpae matua ki tēnei ko te matūkai whakahaumako mai i te rāngai ahuwhenua. He rerekē te urupare o te ngaronga matūkai ki ngā momo āhuatanga, tae atu ki te whakahaeretanga me te āhuarangi. He uaua te inei te ngaronga o ngā matūkai, ā, e kore e taea te kapo ake i te whānuitanga o ngā momo āhuatanga tērā pea ka tātu ake. Nō reira e tuku āheinga ana ngā tauira ki te whakatau tata i ēnei ngaronga. Mai i te tirohanga Māori, ko te tiaki i a Papatūānuku (ngā rawa māori) te whāinga matua rawa, ā, kei ngā tauira te torohū ki te tautoko i ngā kaitiaki ki te pupuri i te mana me te mauri o Papatūānuku. Ko Overseer tētahi tauira e whai ana ki te whakatau tata i ngā rere matūkai ā-pāmu. Kua arotakea e mātau (te Pae Tohutohu Pūtaiao) a Overseer ki te aromatawai mēnā ka tukua e ngā ahunga whakatauira o nāianei te manawanuitanga ki te matapae he aha te pānga o ngā huringa o te whakahaere pāmu ki te ngaronga o te matūkai kai ki roto i te wai. I arotakea e mātou a Overseer i te horopaki o ngā matūkai matua e whai pānga ana ki te tāhawahawatanga o te waimāori. E mōhio ana mātou ki te wāhanga nui o te pūtūtaewhetū i tēnei horopaki, ahakoa nā runga i te āhua o ngā tuhinga o Overseer, tē taea e mātou te tino arotake ake pērā i te hauota.

I whakaritea tēnei arotakenga e te Manatū Ahu Matua me te Manatū Mō Te Taiao, hei urupare ki te pūrongo a te Kaitiaki Taiao a Te Whare Pāremata (PCE) i te tau 2018 me te horopaki o te hōtaka Waimāori Waiwai me ōna whāinga mō te āhua o te waimāori. Ko te pūrongo PCE he wāhanga o te urupare ki te mahi nui ake a Overseer i roto i te waeture waimāori, ahakoa he "pouaka pango". Ka hautō tēnei arotake i te mātauranga Māori me te mahi tauira, ngā pūtaiao ahuwhenua me ngā hihiritanga matūkai. E kore tēnei arotake e whai whakaaro ki te atanga kaiwhakamahi, ngā tauira haurehu kati mahana, tētahi atu āhuatanga rānei o ngā momo taputapu i raro i te waitohu o Overseer, i tua atu i te whakatauira matūkai. Waihoki, kāore te arotake i āta tiro mēnā ka taea te whakamahi i a Overseer hei taputapu pāpori ki te akiaki i ngā kaiahuwhenua ki te whakamahi i ngā rautaki whakahaere taiora, ā, kāore hoki i āta tiro mēnā ka hīkina te pono o ngā tūtohunga a ngā kaitohutohu taiwhenua.

Nā Overseer Ltd rāua ko AgResearch mātau i whakarato ki ngā mōhiohio mō te tauira, tae atu ki ngā mōhiohio kāore i roto i te rohe tūmatanui, kua parengia hei āhuatanga hinengaro a Overseer Ltd. I whai wā mātau ki te kōrerorero i tēnei mōhiohio tauira ki te kaimahi o nga rōpū e rua. I rongo hoki mātau mai i ngā kaiwhakamahi maha o te tauira, me ngā kaimahi o te Kaunihera ā-Rohe o Waikato me te Kaunihera Taiao ki Waitaha. E mihi ana ki te hunga i whai wāhi mai, whai mōhiotanga mai hoki, mō tō rātou anga wairua tuwhera, whaikiko hoki ki te arotake, me tō rātou ngaiotanga.

Te anga o Overseer

I tīmata mai a Overseer i ngā tau o te 1980 e whakarato tohutohu wā roa ana mō te pūtūtaewhetū me te kotakota, ā, kua hia tau nei e whakawhanaketia ana me ngā painga iti i te paheketanga o te wā. Ka whakamahia e Overseer ngā mōhiohio whakanao taketake, matapae rānei (hei tauira, ngā hua kararehe, hua hauhake) i tautuhia e te kaiwhakamahi hei tātai anō i te tipunga tipu, hāunga i te whakamahi tāurutanga āhuarangi i te taha o te āhua o ngā tipu, oneone me te horanuku, i pāhekohekotia ki te whakahaeretanga, hei matapae i te tipunga o ngā tipu. I muri i te tātai anō i te tipunga tipu, ka whakamahi te tauira i tēnei hei tautuhi i te wai oneone me te hiahia matūkai. E whakamahia ana ēnei i ngā tātaitanga o ngā nekeneketanga o te wai me ngā matūkai. Nā reira, kāore e pā torotika ana te tipuranga tipu ki te huarere, ki te wai oneone e wātea ana, ki te matūkai rānei. E whakawhirinaki ana a Overseer ki ngā kaiwhakamahi hei whakamārama taketake i te mahi huanga kai, tae atu ki te nui o te wairākau e ruiruitia ana e riro mai ai aua putanga hua.

He painga te whirinaki o Overseer ki ngā whakaputanga ahuwhenua i tautuhia e ngā kaiwhakamahi, ki te pai o te whakamahinga o te taputapu nā te mea e whakamahi ana i ngā mōhiohio e wātea ana ki ngā kaipāmu. Ka taea e ngā kaipāmu me ngā kaitohutohu te whakatau tata i te ngaronga matūkai mai i ngā tauari whakahaere pāmu me te iti noa o ngā whakangungutanga o te whakamahi tauira. E whirinaki ana a Overseer ki ngā kaiwhakamahi ki te whakarite he tūturu ngā tauari, tērā e tango ana i te hiahia o te tauira ki te matapae i ngā putanga taurangi kua mōhio kē peā ngā kaiwhakamahi (hei tauira, ā rātou whakaputanga i ngā tau kua taha ake).

E whai ana a Overseer ki te whakarato i te whakamāramatanga ine rahi o ngā nekeneketanga matūkai pāmu. I te mea ko te aronga o tēnei arotake ko te kounga o te waimāori, e arotahi ana ki te hauota me te pūtūtaewhetū. Ko te āhua nei, e tōkarikaritia nuitia ana a Overseer ki te whakatau tata i te whakapākekatanga o te pākawa ota i te rerenga wai oneone, engari ka urupare ngā pūnaha hauropi ki te tapeke o ngā ngaronga matūkai mai i te pāmu, ehara i te momo kotahi o te hauota. He āhuatanga tino whaitake hoki tēnei i ngā horanuku e kīia ana kāore i tika te pūheketanga, i ngoikore rānei te pūheketanga o te oneone, otirā neke atu i te 50% tērā o ngā whenua pai o Aotearoa.

Te hanganga me ngā raraunga o Overseer

Ka taea e Overseer te whakamahi aunoa i ngā huinga raraunga (hei tauira, raraunga āhuarangi me te oneone). Mā te whakamahi aunoa i ngā huinga raraunga e whakapai ake i te āheinga me te whakaiti i te pūkawenga o te kaiwhakamahi ki te rapu raraunga kāore pea e wātea noa ana (hei tauira, ngā āhuatanga oneone). Ka whakamahia e Overseer tētahi kōnae raraunga āhuarangi toharite wā roa i hangaia e Taihoro Nukurangi (NIWA) mō ngā tau 1981 ki te 2010. E whakahaeretia ana i runga wāhipa ā-marama, hāunga te tauira mātai arowai, e whakamahi ana i te wāhipa ā-rā. Ngā hua mō pūheke wai atu ki ngā uara ā-marama hei whakamahinga i ētahi atu tātaitanga.

Ka tau tēnei hanganga i runga i ngā whakapae maha.

- Ka whakapae a Overseer i ngā tāurutanga tūturu, whaitake hoki; e whirinaki ana ki ngā kaiwhakamahi anō ki te hihira kei te tūturu ngā pūnaha pāmu. Ahakoa he whāinga whaitake tēnei i te wā e whakamahi ana i ngā raraunga tawhito hei whakarite i te ngaronga matūkai mō tētahi pūnaha pāmu o mua, e whakawhāiti ana tēnei i te pai o te whakamahi i te tauira mō ngā tauari 'ka pēhea', i te wā e matapaetia ana ngā putanga ki ngā āhuatanga e rerekē ai te tōtika.
- E whakapae ana a Overseer i ngā whakaritenga whakahaeretanga pai katoa.
- E matapae ana a Overseer i te noho tūturutanga o ngā āhuatanga me te waikanaetanga-pūmau o te pūnaha pāmu; e matapaetia ana te noho waikanae o ngā tāurutanga pūnaha pāmu (hei tauira, wairākau, hāwaiwai me te kai) me ngā āhuatanga whenua ki ngā whakaputanga o te pāmu.

E whakaputa ana a Overseer i ngā toharite ā-tau wā roa, me ngā kaiwhakamahi e tautuhi ana i ngā whakahaeretanga toharite, ngā tāurutanga me ngā whakaputanga hei tuku whakataunga tata o ngā ngaronga matūkai toharite wā roa. E kore a Overseer, e kore hoki e whakahau ake, i tana āheinga ki te tatau i ngā ngaronga matūkai pāmu ake mō tētahi tau.

E matapae ana a Overseer, i te paunga o te wā roa (hei tauira te 30 tau), ka ōrite ngā hua o te tauira o ngā tāurutanga āhuarangi toharite me te whakahaeretanga ki ērā ka riro mai mā te whakamahi i ngā tāurutanga tūturu, ā, kātahi ka toharitetia aua hua. Otirā, he pono anake tēnei mō ngā pūnaha paerangi. Waihoki mā te arokore ki te rerekētanga āhuarangi tūturu, kāore e hopukina ngā āhuatanga rerekē o te rerenga matūkai hei urupare ki te āhuarangi, i roto i ngā putanga o te tauira. Hei tauira, i ngā wā tino marangai, ka nui ake pea te wai rere noa, te pūheke wai hōhonu, te ngaronga matūkai hoki, ā, ko ēnei āhuatanga e kore e hopukia mēnā e whakamahi anake ana i ngā tatauranga toharite o te hekenga ua. Tāpiri atu ki ēnei āwangawanga, he uaua te matapae i te hekenga ua toharite i te mea me hopu hoki ēnei i te auau, me te nui hoki o te ua, ā, he nui te rerekētanga o ēnei.

Ko tētahi āhuatanga mīharo o te Overseer, ehara i te mea ka tauritetia e ia te papatipu. Heoi anō, e kore pea e rite te nui o te hauota i roto i te pūnaha i te tuatahi me te hauota i tāpiritia, ki te nui o toe tonu ana i te mutunga iho o te whaihanga, tangohia te nui i tangohia, i ngaro hoki. Ko te tauritenga papatipu he herenga pū o ngā momo tauira e whai ana ki te aroturuki tōtika i ngā nekenekehanga o te wai me ngā matūkai. Ki te kore e tauritetia te papatipu, kāore te kaiwhakamahi e manawanui ki ngā putanga o te tauira, tatū noa ki te ngaronga matūkai mai i te pūnaha.

E tohu ana a Overseer i te oneone hei tirohua kanorite, ā, kāore e hopukina te rerekētanga o te tohanga wai me te matūkai puta noa i te hōhonutanga. Ka whakamahia e Overseer ngā hōhonutanga oneone rerekē mō ngā tukanga rerekē, ā, kāore e whakatauira ana he pēhea te pānga o ngā tukanga, tētahi ki tētahi. Ka taea te hoahoa i tētahi maimoatanga pakari ake mā te whakamahi i te tauira papanga maha mō ngā tukanga katoa. E kore tēnei e whakahau i ngā herenga raraunga nui ake mā te kaiwhakamahi, engari ka āheitia ngā whakamārama tika ake o ngā nekeneketanga wai me te matūkai, me ngā whakatau tata o te ngaronga matūkai.

Ko te tikanga o te whakamahinga o ngā raraunga āhuarangi toharite, ngā tirohua oneone kanorite me te whakakorenga o ngā nekenekehanga hauota haukini me te matū whaiwaro oneone, kāore ngā matapae a Overseer e whai whakaaro ki ngā wāhanga hira pea o te ngaronga matūkai. Āpiti ake, kāore a Overseer i hangaia, i takunetia rānei ki te whakatauira i ngā momo āhuatanga mokorea pēnei i te ua tāngutungutu, i ngā wā maroke nui hoki. He ngoikoretanga nui tēnei nā te mea he kōkiritanga waiwai ngā momo āhuatanga tāmutumutu o te ngaronga matūkai, ā, me uru ēnei momo āhuatanga ki ngā maheretanga ngaronga matūkai o ngā pāmu hei rautaki whakamaurutanga.

He uaua hoki te whakamātau i a Overseer ki ngā raraunga whakamātautau i te mea e whakamahia ana ngā āhuarangi toharite.

Tae mai ki tēnei wā, kua arotahi te nuinga o ngā whakamātautau i Overseer ki te whakataurite atu ki te raraunga whakamātautau. Tērā ētahi pūrongo e whakaatu ana i ngā tauritenga pai i waenga i ngā raraunga whakamātautau me ngā whakatau tata a Overseer. Heoi anō, ina whakataurite i ngā tauira ki ngā raraunga whakamātautau, he mea nui kia whakaatatia e ngā tāurunga tauira ērā e whakamahia ana i te wā whakamātautau. Kāore tēnei e taea mā te tauira e whakamahi ana i ngā raraunga āhuarangi toharite wā roa 30 tau. Ko te whakatauritetanga o ngā pākawa ota toharite whakapākeka wā roa i tātaihia ki ngā raraunga āhuarangi toharite wā roa, ki te whakamātautau whakapākeka o te pākawa ota i inetia i te wā poto (atu ki te rua-toru tau) e whakaaweawetia ana e te āhuarangi tūturu, e kore pea e āwhina, hei tauira, mēnā i whakahaeretia te whakamātautau i te wā o te tauraki. He tino nui ngā wero o te whakamātau i ngā tauira ahupūngao koiora matatini me ngā raraunga whakamātautau, ā, ka uaua te whakamātautau i te hanganga o Overseer ki ngā raraunga whakamātautau. Nō reira, me tino kaha te arotahi ki te tirohanga hanganga tauira ā-roto kia tino mōhio ai he whakakanohi tika ana i ngā tukanga ahupūngao koiora - otirā kua oti i a mātou.

E kore pea e pono ngā whakatau tata o te ngaronga pākawa ota pātahi, pūmau rānei.

I runga anō i a mātau kōrero me ngā kaunihera ā-rohe, ka whakaarohia e rātou, mō tā rātou tono, ehara i te hiahiatanga waiwai te matapae tika i te ngaronga pākawa ota pūmau i te mea e whirinaki ana ngā waeture ki ngā tauritenga pātahi o ngā whakatau tata o te ngaronga matūkai mō ngā momo āhuatanga whakahaere rerekē. Engari, e hiahiatia ana te tika o te tauira ki te whakapūmau i ngā uara pātahi, pūmau rānei. Mā te whakamahi i ngā uara pātahi e whakakore anake i ngā haukumetanga o ngā tauira i ngā wā mokorea e ōrite ana ngā haukume, ā, e anga ana ki te ahunga ōrite i ngā āhuatanga whakahaere e rua. Engari mēnā he rerekē te tika o te tauira mō ngā āhuatanga e rua, kāore he pūtāhui ka pono ake i te uara pūmau. Nō reira ehara pea a Overseer i te taputapu pono mō te matapae i ngā whakatau tata o te ngaronga matūkai pātahi, pūmau rānei.

Te Whai Wāhi ki te Māori

Puta noa i te whanaketanga o te tauira, kāore he whai wāhitanga ki te Māori. He tohu tēnei o nga take pūnaha whānui ake i roto i te pūnaha pūtaiao o Aotearoa. E mōhio ana mātou kua tīmata a Overseer Ltd ki te whai wāhi atu ki te Māori ina tata nei mā te tautoko i ngā pakihi ahuwhenua Māori ki te whakamahi i te taputapu. Heoi anō, e whakamahia ai tētahi tauira i roto i te waeture i Aotearoa, me whai wāhi atu, me ako hoki ngā kaiwhakawhanake i te Māori puta noa i te tukanga.

Mai i tētahi tirohanga Māori, ko te whakahekenga o te pānga taiao ki te ētahi pokenga kotahi, e rua rānei, e raruraru ana. Ko te whakamahinga o ngā tauira – me ngā tepenga whakaiti - me mahi hoki i roto i te horopaki o tētahi tātaritanga torowhānui ake o te taiao. Ka hoahoatia ngā tauira hei whakatauira i ētahi āhuatanga taiao, horanuku hoki, engari ka whai katoa ngā tauira i ētahi horanuku kāore i te hāngai ki te tauira. Me ātete rawa i te hiahia ki te whakangāwari ake i te ao tūroa kia māmā ake ai te whakahaere, mā te whakamahi i ngā tauira me te kore e aro ki ngā uauatanga hōhā o ngā horopaki ahuwhenua, taiao hoki.

He taumaha ake ngā āwangawanga hananga i ngā arorautanga o ngā tauira iti

Ahakoa he tauira māmā mā te kaiwhakamahi te atanga kaiwhakamahi o Overseer me te whakamahinga o ngā inenga whakaputanga tūturu, kāore i hoahoatia i te tuatahi mō te whakatau tata tika i ngā ngaronga mātukai. Nō reira, kāore tōna hanganga e tino tohu ana i ngā nekenekehanga pūnaha matatini e pūtake ana i te ngaronga matūkai, ā, e whakatiki ana tēnei i te manawanuitanga ki ōna putanga. Ko ō mātou tino āwangawanga mō Overseer:

- He tauira tūnga mārō e ngana ana ki te whaihanga i tētahi pūnaha nekeneke tonu, e whakaehu tonu ana;
- Ka whakamahi i ngā hipanga-wā ā-marama;
- Ka whakamahi i te raraunga āhuarangi toharite, ā, nō reira, kāore e taea te whakatauira i ngā āhuatanga tāmutumutu, te hopu rānei i ngā urupare ki ngā rerekētanga āhuarangi.
- E kore e tauritetia te papatipu;
- Kāore e aro ana mō te rerekētanga o te tohanga wai me te matūkai i roto i te tirohua oneone.
- Kaore i te tika te whai whakaaro ki ngā otaota pakiaka hōhonu;
- He arotahi ki te pākawa ota, ka hapa te hauota haukini me ngā nekenekehanga matū whaiwaro; ā,

- Kāore he whakaarotanga ki te kawenga o te wai mata me te matūkai, ngā take waiwai o te horanuku ānō hoki.

Ko te hua o ēnei āwangawanga, kāore mātou i te manawanui ki ngā putanga whakatauira o Overseer, ki te kōrero mai mēnā ka heke, ka piki rānei te ngaronga matūkai i ngā panonitanga whakahaere pāmu, he aha rānei te nui o te hapa o ēnei ngaronga. Ahakoa ko ētahi o ngā waehanga o Overseer he pono te āhua, pēnei i te tauira iti o te pūngao whakarau a te kararehe, he nui kē atu ngā raruraru hanganga torowhānui i ēnei arorautanga. Nō reira e whakaaro ana mātou kāore e tika ana te hanganga o Overseer hei whakarato i te māramatanga nui ake i tētahi mea whānui rawa mō ngā ngaronga matūkai o te pāmu (hāunga mō te rere o te wai mata i te mea kāore ēnei i roto i te tauira). Kāore e taea te whakatau tata tōtika he pēhea te pānga o ngā panonitanga whakahaere pāmu ki aua ngaronga.

Ko ngā mahi anamata hei āwhina i te whai māramatanga, te ine rahi me te whakaiti i ēnei ngaronga, ka uru pea te whanaketanga o ngā tauira ahupūngao koiora, i te taha pea o ngā taputapu tautoko i ngā whakatau māmā. Tērā pea he āhuatanga o te tauira o Overseer, pēnei i te atanga kaiwhakamahi, ka whai wāhi atu ki te whanaketanga o ēnei taputapu. Kāore e kore ka whai whakaarotia ngā take maha e ngā whakataunga o te ahu whakamua, engari me kōkiri anō i runga i te whakaaro he aha te huarahi ki ngā putanga pai rawa mō te kounga o te waimāori i Aotearoa.

Part 1: Introduction

1 The panel's process

The Science Advisory Panel has robustly assessed Overseer's modelling approach. The Ministry for Primary Industries (MPI), the Ministry for the Environment (MfE), the Prime Minister's Chief Science Adviser, and the chief science advisers of MPI and MfE appointed a team of independent experts to cover all relevant skillsets and ensure demographic representation. Throughout the review, the panel discussed the Overseer model with AgResearch, Overseer Ltd, and regional councils. Officials from MPI and MfE provided further context. The panel had access to all of Overseer Ltd's technical manuals, including those that are not publicly available, and conducted a complete and thorough review.

1.1 CONTEXT

The degradation of freshwater is a key environmental challenge of our time. Aotearoa New Zealand has a major problem with water quality due to diffuse nutrient losses from farms (PCE, 2018). These diffuse pollutants include fine sediments, pathogens, and nutrients (Howard-Williams *et al*., 2010). Nutrients of concerns are total nitrogen and total phosphorus. Total nitrogen is all forms of nitrogen, including nitrate and ammonia. Both can have serious effects on water quality (MfE, 2020c). As these diffuse nutrient discharges cannot be readily measured, models are used to estimate losses from farm systems. Overseer is the model most widely used to estimate farm nutrient flows in Aotearoa New Zealand.

1.2 PANEL MEMBERS

MPI and MfE established a long list of candidates for membership of the panel. Overseer Ltd and members of the public were given the opportunity to suggest candidates and MPI and MfE screened the long list against exclusion criteria:

- Candidates who had been directly involved in the development of the Overseer model were not considered.
- Candidates who had undertaken previous work with Overseer were considered on a case-by-case basis.
- Candidates who were employed by Overseer Ltd or the Overseer owners were not considered.
- Candidates who had been occasionally contracted by Overseer Ltd or the Overseer owners were considered on a case-by-case basis.
- Candidates who had previously expressed strong positive or negative opinions about Overseer were not considered.

MPI and MfE then ranked the suitability of candidates as high, medium, or low. Candidates with high or medium suitability were contacted to enquire about their interest and availability, and to determine whether there were any conflicts of interest. Those who indicated they were available, interested, and had no conflicts of interest were added to a shortlist. A selection panel met in November 2019 to review the shortlist. They concluded that several shortlisted candidates were highly suitable, but skill gaps and a lack of diversity remained. The number of panel members was increased to cover a wider range of skillsets and allow for greater representation.

The selection panel

Dr Allison Collins – Ministry for the Environment's Kaitohutohu Mātanga Pūtaiao Matua
Professor Juliet Gerrard – The Prime Minister's Chief Science Adviser
Dr John Roche – Ministry for Primary Industries' Chief Science Adviser

It was agreed that the panel membership would include three members who are primarily modellers, alongside supporting scientists with an interdisciplinary range of skills including: agronomy, animal nutrition and physiology, crop and livestock systems, hydrology and drainage, mātauranga Māori and Te Ao Māori, Aotearoa New Zealand farming systems, nutrient cycles and biogeochemistry, regional council experience, and soil science. MPI conducted a targeted search to address skill and demographic gaps. The final panel membership was agreed on 17 December 2019 and publicly announced on 11 March 2020. Following the first workshop in March 2020, the panel tabled a Register of Interests summarising any interests that could potentially relate to the Overseer review.

The Overseer Science Advisory Panel

Dr Ian Johnson
Dr Johnson is a mathematician with experience in developing and writing biophysical computer simulation models incorporating environmental physics, plant, crop and pasture growth, soil hydrology, soil organic matter and nutrient dynamics, and animal growth and metabolism. Early in his career he was with the Biomathematics Department at the Grassland Research Institute in the UK and then the Department of Agronomy and Soil Science at the University of New England in Armidale, NSW. More recently, as director of IMJ Consultants, he has developed models in collaboration with universities and industry bodies in Australia and New Zealand. He is widely published in the scientific literature, including as co-author of the textbook Plant and Crop Modelling (Thornley and Johnson, 1990, 2000).

Dave Clark
Dave Clark is a dairy industry and research consultant. Between 1991 and 2013, he was Principal Scientist at the Dairying Research Corporation/Dexcel/DairyNZ. His research during that time looked at the intersection of farm economics and environmental impact, and was underpinned by a philosophy that environmental protection and profitable dairy farming are not mutually exclusive. In 2009 he was awarded the New Zealand Grassland Trust – Ray Brougham Trophy for services to New Zealand farming systems. He carried out mainly hill country research when he worked at Grassland Division, Department of Scientific and Industrial Research in the early stage of his career.

Dr Brent Clothier
Principal Scientist with Plant & Food Research, Dr Clothier has extensive experience in soil science, especially with the measurement and modelling of water and solute movement in soil. He has published more than 300 peer-reviewed publications.
He was elected a Fellow of the Royal Society Te Apārangi in 1994 and was the President of the New Zealand Society of Soil Science from 2008 to 2010. He is an Academician (Foreign) of the Chinese Academy of Engineering (Agriculture Division).

Dr Donna Giltrap
Currently Research Priority Area Leader for Agricultural Greenhouse Gases Emissions and Mitigation at Manaaki Whenua – Landcare Research, Dr Giltrap is a modeller with a background in physics and mathematics. Her PhD is in physics and she also holds a Graduate Diploma in Applied Statistics. She was part of the team that reviewed the nitrous oxide component of Overseer in 2018. She is a member of the New Zealand Soil Science Society.

Dr Clint Rissmann
Dr Rissmann is the founder and Director of Land and Water Science Ltd. He is also a Senior Adjunct Fellow in the Waterways Centre for Freshwater Management – a partnership between the University of Canterbury and Lincoln University. He has more than 10 years' experience in earth systems science, specialising in water quality, biogeochemistry, greenhouse gases and systems thinking. He has co-authored a number of peer-reviewed publications researching soil and water quality in New Zealand.
He is a leading proponent of the physiographic approach which involves understanding water quality outcomes based on an integrated understanding of landscape properties.

Dr Nick Roskruge
Dr Roskruge is of Atiawa ki Taranaki and Ngāti Tama-ariki descent. He is Professor in Ethnobotany at Massey University, and since 2003, has been Chairperson of Tāhuri Whenua, which represents Māori interests in the horticulture sector. He is a member of the Māori Advisory Board for Resilience to Nature's Challenges – a National Science Challenge - and is also a member of the HSNO Committee of the Environmental Protection Authority (EPA). Previously he was Chair of Ngā Kaihautū Tikanga Taiao, the EPA's Māori advisory committee.
He holds a PhD in soil science with his doctoral thesis looking at Māori land development through traditional knowledge, and the soil and horticultural sciences. He has had sabbatical periods in Peru and Chile, where he worked on crop genetics and indigenous systems projects. He was the 2013 recipient of a Fullbright Scholarship, undertaken at Cornell University (USA).

The Overseer Science Advisory Panel - continued

Dr Peter Thorburn
Dr Thorburn is a Chief Research Scientist and Research Group Leader in the Commonwealth Science and Industrial Research Organisation (CSIRO) in Queensland. He is responsible for agricultural systems research and is internationally recognised for his expertise in crop systems modelling.
He represents CSIRO on the Agricultural Production Systems Simulator (APSIM) initiative, which owns the APSIM advanced farming systems model, and is co-lead for crop modelling in the international AgMIP program. He has extensive experience in scientific advisory groups, including as a member of groups on managing water quality in Great Barrier Reef catchments and reviewing or advising on Overseer in 2012 and between 2014 and 2017.

Dr Robin White
Dr White is Associate Professor of Integrated Beef Systems Management at Virginia Tech in the United States. She is a member of the American Dairy Science Association, an editor for the Farm Systems Analysis and Economics and Resources and Environment sections of the Journal of Dairy Science, and an Editorial Board member of the Journal of Animal Science.
Her research focuses on leveraging data analysis and animal nutrition to enhance the sustainability of food production systems. She graduated from Washington State University as a Doctor of Philosophy in Animal Sciences.

1.3 SCOPE OF THE REVIEW

MPI and MfE appointed a team of independent technical experts to review the Overseer model. This is necessary to assess whether it can confidently be used as a decision support tool and in a regulatory context. These contexts will be discussed further in Chapter 2. The overall objective of the peer review was to conduct an independent scientific assessment of the model, including aspects of the model that are commercially sensitive and protected by intellectual property rights.

The review was initially structured in two phases. The first phase, the results of which are presented in this report, assessed Overseer's overall modelling approach. The panel conducted this assessment directly.

The peer review was:

- **Independent**. It was undertaken by objective experts, independent of the original model developers, Overseer owners, and Overseer Limited.
- **Interdisciplinary**. It involved environmental modellers and scientific experts from multiple disciplines.
- **Comprehensive**. It addressed the overall modelling approach.
- **Transparent**. Reports and key documentation were and will be published.

The panel was tasked with assessing whether Overseer's current modelling approach (including key design principles and assumptions) is fit-for-purpose to model nutrient flows associated with Aotearoa New Zealand farm systems, in the context of:

- its current use as a decision support tool for land- users, and
- its current use as a regulatory tool by regional councils following recommended guidelines, across different sectors (6a and b of the Terms of Reference)[1].

It was out of scope of this review to look at Overseer's modelling of greenhouse gases (see Kelliher *et al.* (2015) and de Klein *et al.* (2017) for more information). Overseer's user interface, the data files collated, and the effectiveness of Overseer in encouraging farmers to adopt nutrient management strategies were also outside of our scope.

More detail on the structure and scope of the review is available at https://www.mpi.govt.nz/agriculture/land-care-farm-management/overseer/technical-review-of-the-overseer-model/.

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[1] During the inception workshops, MFE, MPI and regional council staff described what is required from Overseer as a freshwater regulatory tool, where councils are following best practice guidelines. These presentations are available on the MPI website.

1.4 WORKSHOPS

1.4.1 Inception workshop

The panel held their inception workshop over Skype during COVID-19 Alert Level 4 on 30 and 31 March 2020. This workshop focused on setting the scene for the review. They discussed the scope of the review, their responsibilities, and how to work together. They heard from Overseer Ltd, who demonstrated OverseerFM and the user interface and introduced Overseer Ltd's science strategy. Representatives from Environment Canterbury and Waikato Regional Council described how they use Overseer. The original developers of the Overseer model from AgResearch introduced Overseer's modelling approach. The panel focused on discussing the original development principles, climate inputs, biophysical inputs, and model outputs.[2]

After the workshop, panel members prepared reflections on progress to date, and had a short follow-up meeting to discuss the reflections and determine next steps. They then provided follow-up questions to AgResearch to confirm their understanding of aspects of the model approach.

1.4.2 Model Approach workshop

The panel held their next workshop on 29 and 30 June 2020, with half able to attend in person in Wellington. The rest attended over Skype. This workshop focused on establishing a clear understanding of the modelling approach and the context of Overseer's use in regulation. They heard from MfE officials and staff from the Parliamentary Commissioner for the Environment's (PCE) office who discussed the wider context of freshwater and the regulation of diffuse agricultural discharges. They also heard more from AgResearch and had deeper discussions about climate, animal metabolism, pasture and crop production, and nutrient dynamics. They discussed the drafting of this report and began to come to conclusions regarding Overseer's fitness for purpose.

1.5 ACCESS TO INFORMATION

The panel was provided with contextual information to support the review, listed in Table 1.1 below. MPI and MfE provided context on the use of Overseer in regulation and peer review work done to date. They also read the PCE report (PCE, 2018) and Overseer Ltd's description of Overseer for regional councils (Watkins and Selbie, 2015). They had access to Overseer Ltd's published and unpublished technical manuals and additional unpublished documents through a Sharepoint portal. The Secretariat and panel asked for any relevant information throughout drafting the report. When the first draft was being fact-checked by Overseer Ltd and the Overseer owners, they referenced additional documents which were eventually provided to the panel.

Table 1.1 Access to Information

Contextual information	
Stocktaking report summarising peer review work to date	MPI[3]
Overseer and regulatory oversight: Models, uncertainty and cleaning up our waterways	PCE (2018)
Overseer Ltd's *Technical Description of Overseer for Regional Councils*	Watkins and Selbie (2015)
Existing guidance on the use of Overseer in regulation	MPI[4]
Different approaches to use of Overseer in regional plans	MfE (2020a)

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[2] Presentation slides from the inception workshop are available on the MPI website www.mpi.govt.nz

[3] Available at https://www.mpi.govt.nz/dmsdocument/41160-mpi-secretariat-report

[4] Available at https://www.mpi.govt.nz/dmsdocument/41145-report-on-appropriate-use-of-overseer-in-regulation

Technical information			
Published technical manual chapters:		Confidential technical manual chapters:	
Introduction	Wheeler (2016)	Animal intakes	Wheeler (2018a)
Animal metabolisable energy requirements	Wheeler (2018b)	Animal model	Wheeler (2018c)
Carbon dioxide, embodies and other gaseous emissions	Wheeler (2018f)	Block nutrient budgets phosphorus and sulphur	Wheeler (2017)
Characteristics of animals	Wheeler (2018g)	Characteristics of crops	Wheeler (2018h)
Characteristics of fertilisers	Wheeler and Watkins (2018a)	Crop nitrogen model	Wheeler (2018l)
Characteristics of pasture	Wheeler (2018i)	Effluent management	Wheeler (2018n)
Characteristics of soils	Wheeler (2018j)	Inter block distribution	Wheeler (2018m)
Climate	Wheeler (2018k)	Urine patch	Wheeler (2018q)
Hydrology	Wheeler (2018o)		
Calculation of methane emissions	Wheeler (2018d)	Additional confidential documents:	
Calculation of nitrous oxide emissions	Wheeler (2018e)	Analysing and monitoring farm systems with Overseer Ltd	
Supplements	Wheeler and Watkins (2018b)	Overseer science model description	

Information provided later			
Published		Confidential	
FRNL-Overseer integration: Completed evaluation of FRNL data against Overseer	Shepherd *et al.* (2019)	A review of the Climate and Hydrology modules in Overseer	Horne (2014)
Reviewing and revising the DCD model within OVERSEER® nutrient budgets	Shepherd *et al.* (2012)	Precision of estimates of nitrate leaching in OVERSEER®	Ledgard and Waller (2001)
Comparing OVERSEER® estimates of N leaching from grazed winter forage crops with results from Southland trial sites	Smith and Monaghan (2013)	Review of fitness of purpose of the OverseerFM model	Mockler (2021)
A comparison of APSIM and OVERSEER predictions of nitrogen leaching from a well-drained soil under a dairy farm	Vibart *et al.* (2015)	Evaluation and validation of the OVERSEER drainage model (v. 6.3.1)	Shepherd (2019)
Comparison of OVERSEER and IrriCalc predicted irrigation and drainage depths	Wheeler and Bright (2014)	Evaluation and validation of the OVERSEER pastoral background N leaching sub-model (v. 6.3.1).	Shepherd and Selbie (2019)
		An evaluation of the OVERSEER urine patch N Leaching sub-model	Shepherd and Selbie (2020)
		Overseer® design and its effect on timescales	Wheeler *et al.* (2018)

2 The history of Overseer and its use

2.1 ORIGINAL MODEL DEVELOPMENT

Overseer is a computer software model that estimates nutrient use and transfers and losses within a farm system. It is used to provide information on nutrient losses from farms and aims to support strategic decision-making for farmers (Muirhead, 2020). Specifically, Overseer estimates nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, sodium, and greenhouse gas emissions (Watkins and Selbie, 2015).

Overseer assumes actual and reasonable model inputs, given that it is based on real farm data. It also assumes steady state conditions (Watkins and Selbie, 2015).

Overseer's design principles (Muirhead, 2020)

Overseer was designed to be a farmer-centric model, not a science model for scientists.

Overseer uses information that a farmer or fertiliser representative can readily access:
- Stock numbers
- Crops sown
- Fertiliser applications
- Imported feed
- Outputs (e.g., meat, milk, wool, feed, crop yield)
- Soil tests

This information is supported by:
- Default values that can be overridden if the farmer has better information
- Databases: Climate data (NIWA), Soil data from S-map (Manaaki Whenua)

The first iteration of Overseer was the Computer Fertiliser Advice System (CFAS), created in the 1980s. This was revised into Outlook Phosphorus & Sulphur in 1996. Nitrogen and potassium were added to the model to create Overseer Nutrient Budgets (Overseer version 2). It modelled nitrogen, phosphorus, potassium, and sulphur. It only considered one management unit at a time and could not model camp areas[5]. Overseer version 3 was created in 2000. Overseer was updated to version 4 in 2002 to include modelling of effluent and supplements. Version 5 was created in 2003; calcium, magnesium, and sodium were added, as were greenhouse gases and energy reports and mitigation options. The model also moved to a monthly time-step, but still produced long-term annual averages. In 2012, with version 6, there were major upgrades to irrigation modelling and the S-map soil database. In 2019 OverseerFM was developed, which had an updated user interface (Muirhead, 2020; PCE, 2018; Watkins and Selbie, 2015). Overseer's history is summarised in Table 2.1.

S-map (Lilburne *et al.*, 2020)

S-map is New Zealand's digital spatial soil database, managed by Manaaki Whenua. It brings together older reports and databases and includes updated soil maps. S-map is New Zealand's best available soil knowledge in the absence of a professional farm soil survey. It is a key input into Overseer; it improves Overseer's estimates where it is available. It currently covers 62% of productive land, but there are still large gaps.

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[5] Camp areas are the areas in a paddock where animals spend most of their time. For example, in a flat paddock with minimal shade animals might congregate under a tree, or in hill country they might congregate on flatter areas.

Table 2.1 Timeline of Overseer's development (Watkins and Selbie, 2015)

Year	Model	Description	Outcome
1982-84	CFAS	Summarised all available fertiliser research and provided standardised fertiliser advice	Estimated fertiliser requirement based on calculated inputs and outputs
1996	Outlook	Incorporation of results from the analysis of datasets summarising all phosphorus, potassium, and sulphur field trials in Aotearoa New Zealand	Improved predictions of plant nutrient concentrations and relative yield; inclusion of economic information
1999	PKSLime model	Addition of lime trial information	Capital lime recommendation model added
2000	Overseer 2	International concern about the role of farm nutrients in environmental degradation required the estimation of nitrogen loss	First publicly available nutrient budget model; environmental focus on nitrogen; development of separate crop and horticultural models
2000	Overseer 3	Combined PKSLime model and Overseer 2 into a single model (this is now known as the econometric model, which is a proprietary software)	Productivity, econometric and environmental model
2002	Overseer 4	Overseer 2 was expanded to include environmental reports, winter management options and a wider crop range; block scale model	Winter management options; wider crop range
2003	Overseer 5	The first whole farm system nutrient budget model; could predict transfers of nutrients between different management blocks	Additional nutrients (calcium, magnesium, sodium), acidity, greenhouse gas and energy resource reporting; monthly animal inputs; scenario analysis; additional reports
2005-09	Overseer 5.2-5.4	Increased use in evaluating farm management effects on nutrient flows and environmental emissions; interest in possible regulatory role	Addition of phosphorus runoff loss model, fodder crops, pig effluent and house blocks; pad system upgraded including the addition of animal shelters and effluent management systems; inclusion of nitrification inhibitors, wetlands and riparian strips; crops and horticultural models overhauled
2012	Overseer 6	Integration of all models into a single model; development of a new architecture	Pasture, crops, horticultural blocks all linked into one model; addition of cut and carry blocks and dairy goats; upgrade of irrigation and effluent management system; introduction of monthly nitrogen leaching model; life cycle assessment methods for greenhouse gas emissions

Overseer is increasingly applied in contexts outside the scope of the original design principles of CFAS. These are discussed in 2.2 and 0 below.

2.2 USE IN REGULATION

As well as CFAS's original intended use for decision support, Overseer came to be used by regional councils for the regulation of diffuse discharges to freshwater, through regional plans promulgated under the Resource Management Act 1991 (RMA). Overseer was first used in regulation in 2005, when Waikato Regional Council notified Variation 5 of its regional plan relating to the Lake Taupō catchment. In 2007, Horizons Regional Council became the first region to use Overseer in its regional plan across catchments.

There is some existing guidance to regional councils on the use of Overseer in the regulation of diffuse discharges (Freeman *et al.,* 2016; Willis, 2018). The most appropriate use of Overseer depends on specific catchment characteristics, local water quality issues, the available information, and the resources available to develop and implement a regional plan (Freeman *et al*., 2016). However, existing guidance identifies key themes for how Overseer should be used in regulation:

- Overseer modelling should be in accordance with Best Practice Data Input Standards.[6]
- People using Overseer for compliance and auditing should be qualified (e.g., the Massey University Certificate in Advanced Sustainable Nutrient Management). Overseer modelling requires expert knowledge of Aotearoa New Zealand farming systems and Overseer's modelling approach and assumptions.
- Overseer's estimates should be interpreted as long-term average nitrogen leaching rates, as Overseer uses 30-year average climate data. Even if annual farm data are used, the estimate does not represent actual leaching in that year.
- To assess compliance with a regional rule or resource consent condition, a rolling average of 3-5 years of Overseer outputs should be used to represent long-term nutrient loss.
- Plans must include mechanisms to manage Overseer version changes, by:
- Assessing the implications of updates for catchment-scale nutrient loads;
- Avoiding the use of fixed numerical limits;
- Including a mechanism to update nutrient loss thresholds, limits, and estimates as Overseer versions change; and
- Where Overseer is used at multiple stages in a planning process, Overseer versions must be consistent.
- Overseer is best used to assess relative differences in nutrient losses, rather than estimating absolute values, to minimise the risks associated with model uncertainty.
- Overseer should not be used as a pass/fail tool to demonstrate compliance against specific nutrient loss limits.
- Overseer can be used in a relative sense to compare nutrient loss over two separate time periods using the same model version, require a percentage improvement over a benchmark, or compare nutrient loss estimates between different future farm management scenarios.
- Overseer estimates can be used as a trigger for increased scrutiny, should they exceed a threshold value.
- Overseer should be used in combination with other mechanisms to manage water quality (e.g., Farm Environment Plans (FEPs), Good Management Practices, measurements of environmental effects in receiving water bodies).
- Overseer does not model all farm management practices. These gaps need to be managed.
- Overseer assumes that a farm system is in steady state. It therefore should not be relied on when a farm is going through a transition period (e.g., land use change).

Regional councils use Overseer is various ways (see Table 2.2; MfE, 2020a) and do not necessarily base their use on existing guidance.

Table 2.2 Approaches to the use of Overseer in planning documents

Approach	General description	Councils
No regulatory usage	No explicit reference to Overseer in regulatory plans	Northland Regional Council Taranaki Regional Council Marlborough District Council Greater Wellington Regional Council Nelson City Council Tasman District Council West Coast Regional Council

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[6] For the most recent version of Overseer (OverseerFM), the Best Practice Data Input Standards are incorporated into the User Guide: https://docs.overseer.org.nz/fm/OverseerUserGuide.pdf. Related resources can be found at https://www.overseer.org.nz/support-and-training

Informational use or trigger for resource consent	Preparation of Overseer nutrient budget required as part of permitted activity status	Auckland Regional Council Gisborne District Council Environment Southland: • Permitted activity status requires preparation of a FEP containing Overseer Nutrient Budget • FEPs do not require council approval but must be provided on request • Intended to support subsequent decision-making under tighter limits
	Overseer nutrient loss estimates used as threshold for resource consent	Example: Hawke's Bay Regional Council – Tukituki catchment • Permitted activity status requires a nutrient budget within a FEP • If an Overseer nutrient loss estimates exceeds a trigger (x kg N ha^{-1} y^{-1}) a consent is required.[1] • The consent triggers a nitrogen reduction process through the implementation of progressively more stringent management practices.
Used to derive or set limits	Overseer is used in conjunction with catchment and attenuation models to help set catchment level limits	Various uses are often not disclosed.
	Overseer nutrient loss estimates are used in conjunction with administrative decisions to set farm level limits or reductions	Bay of Plenty Regional Council – Lake Rotorua • Land use is grouped into sectors • Overseer is used to model average historic nitrogen losses from a four-year reference period • The current limit is based on a percentage reduction from the reference period, with sector average benchmarking to target higher leaching properties. Environment Canterbury • Requires a percentage reduction from historic losses. • In the Hinds/Hekeao Plains area, properties exceeding 20kg N ha^{-1} y^{-1} are required to progressively lower their discharge (15% by 2025, 25% by 2030, 36% by 2035) but they are not required to reduce losses below 20kg N ha^{-1} y^{-1} and can increase losses up to 15kg N ha^{-1} y^{-1}. Waikato Regional Council – Plan Change One[2] • Nitrogen leaching numbers for each FMU (Freshwater Management Unit) are an activity status trigger, along with input controls varying by land use activities. • Activity status triggers FEP requirements, including requirements to demonstrate nitrogen loss leaching rates.

		Horizons – Manawatū • Cumulative nitrogen leaching maxima are set for targeted catchments and allocation limits are set according to LUC class. • Overseer numbers are used to establish a threshold for consent depending on the intensity of production • All consent types require a Nutrient Management Plan.
Used as part of a broad/semi-flexible approach to compliance	Overseer is used in conjunction with a certified/audited FEP to model a reduction pathway and make an administrative or professional assessment of compliance	Environment Canterbury • Activity status depends on land use • Consent requires a FEP which includes a nitrogen loss limit • Consent conditions require farm to obtain an A or B grade on their FEP audit, where auditors ask: • Is the farm implementing good management practices? • Is the farm complying with the nitrogen limit/Overseer estimate?
	Overseer is used in conjunction with a Nitrogen Management Plan (NMP) with an associated Nitrogen Discharge Allowance (NDA)	Waikato Regional Council – Lake Taupō Plan Variation 5 • The total NDA is set using Overseer-based farm data from 2001-2005. • Farmers develop a NMP which sets out farm system parameters. • Overseer predictions the farm's nitrogen loss from the NMP, and if it is less than the NDA they hold, then they can do that activity. • The NMP is appended to the farmer's consent and if compliance checks find any parameter to be greater than specified in the NMP, then the system is run through Overseer to check the farm still complies with the NDA. • NDAs can be bought a sold within the catchment to ensure farmers' NDAs match their discharges.

[1] The threshold is based on the Land Use Capability (LUC) class of the land. LUC helps to understand the sustainable production potential of Aotearoa New Zealand's agricultural land. The system rates the versatility of land based on the limitations for use in primary production. LUC class 1 has the fewest limitations and is generally flat, while LUC 8 has the most limitations and is generally very step. In the Tukituki catchment, LUC class 1 has a limit of 30.1 kg N ha^{-1} y^{-1}, whereas LUC class 8 has a limit of 3 kg N ha^{-1} y^{-1}.

[2] At time of writing the Commissioners' decision on the plan change has been notified and is now subject to appeal by submitters.

Activity status (MfE, 2020a)

The rules in a regional plan determine the status of an activity, and therefore whether a resource consent is required. Plan rules must specify whether an activity is:

- Permitted: no resource consent required
- Controlled: resource consent required but always granted
- Restricted discretionary: resource consent required, and regional council has restricted discretion when considering consents
- Discretionary: resource consent required, and regional council has full discretion when considering consents
- Non-complying: resource consent required and granted if the application meets RMA threshold criteria and the objectives and policies of the regional plan. These applications need to be particularly robust.
- Prohibited: resource consent will not be granted.

2.3 USE IN DECISION SUPPORT

According to the Overseer Ltd website (www.overseer.org.nz), OverseerFM[7] helps farmers protect land for the next generation and make decisions about farm nutrient management informed by science, as well as "take control of meeting regulations" (Overseer Ltd, 2020a). Overseer was founded on the aspiration to have a common and approved basis of producing farm nutrient budgets and greenhouse gas reports from detailed farm data. The company states this allows farmers to know which nutrients are needed to maintain soil fertility, measure the nutrient and greenhouse gases that could be lost to the environment, and to test 'what if' scenarios from which to choose the best farm management practices (Overseer, 2017).

Overseer has played a role in supporting farm decision-making for many years. Managing the nutrients coming into, internally transferring, and leaving the farm is one important way of improving the profitability and sustainability of a farm business (Watkins and Selbie, 2015). Other uses include:

- Estimation of maintenance nutrient requirements in pastoral farm systems to make fertiliser recommendations[8] (this is most relevant to phosphorus and lime);
- Providing an estimate of greenhouse gas losses from a farm;
- Scenario testing - testing a range of management changes;
- Identify nutrient hotspots (e.g., high nutrient loss blocks) and optimise effluent block areas to ensure correct amounts of nutrients are being applied.; and
- Benchmarking (Watkins and Selbie, 2015).

2.3.1 Management of farm dairy effluent (FDE)

The management of FDE is an example of the benefit to farmers of using a tool like Overseer to understand their farm system well. Some farmers disposed of FDE directly into waterways, but due to increasing awareness of the environmental effects and tightening environmental regulation, increasingly dispose of it on land instead. Farmers noticed metabolic issues with cattle due to high potassium intake, as land with high concentrations of FDE applied became enriched in potassium. In Overseer, users can input the area they apply FDE to. This helped to illustrate that FDE needed to be distributed over a larger area to reduce potassium concentrations and reduce nutrient loading to a level safe for animals. Understanding the type of soil FDE is applied to is a key factor in this decision, which Overseer enables farmers to consider (R. Muirhead, 2020, personal communication, 23 July).

2.3.2 Decision support and use in regulation

In some parts of Aotearoa New Zealand, Overseer's use in decision support is driven by supporting farmers with regulatory compliance. For example, while the regulator may only use Overseer as an indicator, it will be used to help farmers make investment and management decisions such as whether they can buy a property given the Overseer baseline nitrogen losses associated with the RMA consents for that property. When a farmer is considering purchasing a new block of land in

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[7] OverseerFM is the online software that connects users to the Overseer model.
[8] Overseer is not designed for, and should not be used for, nitrogen fertiliser recommendations.

Canterbury, for example, they likely consider whether it will be a viable business decision given the property's nitrogen baseline. When contemplating farm system change, a farmer can use Overseer to investigate how the change would affect their ability to meet their nitrogen baseline. They might also use Overseer to explore how they could meet necessary nitrogen loss reductions (A. Carlton 2020, personal communication, 23 July). When modelling scenarios like this, users will often use FARMAX (Bryant *et al*., 2010) to estimate the financial consequences of farm management decisions (A. Pemberton 2020, personal communication, 11 August).

2.4 PCE REPORT AND RECOMMENDATIONS

In December 2018 the PCE released the report *Overseer and regulatory oversight: Models, uncertainty, and cleaning up our waterways* (PCE, 2018). The report focused on the use of Overseer as a regulatory tool for freshwater and argued that a greater level of confidence is required for model results used in regulation than those used for decision support for farming purposes.

The report made ten recommendations to ministers and Overseer's owners. The first recommendation asked ministers to indicate if they wish to see Overseer used as a tool in freshwater regulation. A model that can estimate nutrient pollution from diffuse agricultural pollution is necessary to support outcome-based regulation of freshwater quality. MPI and the MfE therefore initiated this independent peer review of Overseer to determine if Overseer can be that model (PCE's Recommendation Three). The PCE also recommended that the Overseer model be made open-source in part due to concerns about a "black box" being used in regulation. It is outside the scope of this review to comment on Overseer's transparency.

In a written response to the PCE, government ministers agreed with all his recommendations, but decisions on open-sourcing Overseer were deferred to be informed by analysis of ownership, governance, and funding arrangements. Some work on the recommendations is already underway, including uncertainty and sensitivity analysis (which Overseer Ltd is leading), but much work awaits the outcome of this review.

PCE recommendations

1. I recommend that the Minister for the Environment and the Minister of Agriculture indicate if they wish to see Overseer used as a tool in the regulation of water quality and, if so, clearly identify what additional steps and actions may be required to support that use.

2. I recommend that the Minister for the Environment task his officials to develop best practice guidance for the development, evaluation, and application of environmental models in regulation, drawing on international experience.

3. I recommend that the Overseer owners and Overseer Ltd ensure that a comprehensive and well-resourced evaluation of Overseer is undertaken. In particular:
    - a whole-model peer review should be undertaken by technical experts independent of those who performed the development work.
    - a formal uncertainty and sensitivity analysis should be undertaken for the Overseer model.
    - In the interests of greater transparency, the following information should be documented and made publicly available:
    - the collated data used to calibrate and test the model
    - the underlying scientific principles for all model components
    - the algorithms, equations and parameters for all model components
    - the source code.

4. I recommend that Overseer owners make Overseer an open-source model.

5. I recommend that the Minister of Agriculture and Minister for the Environment seek advice on ownership, governance and funding arrangements that would:
    - enable Overseer to be mandated as the ‘official’ model for estimating diffuse nutrient pollution for water management purposes where that is appropriate; and
    - secure the ongoing resources to maintain and develop the model.

6. To provide long-term funding stability, I recommend that the Minister of Agriculture and Minister for the Environment direct officials to conduct a strategic review of the:
    - resourcing needed to maintain and develop the model
    - level of ongoing costs appropriately attributable to Overseer users in a regulatory setting
    - level of public-good investment needed to build trust in the model through better corroboration and calibration using a greater number of sites throughout the country
    - basis on which regional councils should contribute to regionally specific research to support use of the model.

7. To this end, I recommend that the Minister for the Environment direct officials, in consultation with regional council staff, scientists, and expert planners, to prepare guidance for councils designing plan provisions that use Overseer as part of a framework involving nitrogen-loss limits.

8. I further recommend that the Minister for the Environment direct officials to initiate a working group including representatives from each regional council and unitary authority, scientists, and Overseer Ltd to undertake a strategic review of:
    - those circumstances where regionally specific research is needed to support use of the model (e.g., field trials to be used in calibration or corroboration)
    - the mechanisms to fund this research
    - ways of ensuring that the outputs of this research are fit for purpose (e.g., the trial duration is long enough) and can be subsequently used in Overseer’s modelling.

9. I recommend that the Minister for Science and Innovation, in consultation with the Minister for the Environment, reviews the ownership, use, and development of the many models and databases that inform our understanding of catchment-scale dynamics, to ensure that water quality managers have access to the best possible understanding of nutrient transport and transformation.

10. I recommend that the Minister for Science and Innovation ensures that the Crown’s ongoing investment in these models and databases is made in a joined-up way, with the express aim of contributing to the goal of protecting ‘the life-supporting capacity of air, water, soil and ecosystems’.

2.5 CONCLUSION

The overall objective of this peer review is to conduct an independent scientific assessment of the Overseer model in the context of its use as a regulatory and decision support tool. This report considers whether Overseer’s current modelling approach is fit-for-purpose to model nutrient flows within Aotearoa New Zealand farm systems for use as a decision support tool for land-users and as a regulatory tool by regional councils following recommended guidelines, across different sectors. For these applications, we need confidence that Overseer’s modelled outputs provide estimates of the direction and magnitude (and associated error) of change in nutrient losses from a farm due to a change in farm management. That is, therefore, the focus of this report.

3 Te Ao Māori and Te Tiriti o Waitangi

Whatungarongaro te tangata, toitū te whenua. As people disappear from sight, the land remains.

Te Tiriti o Waitangi is the core basis of Aotearoa New Zealand's constitution. As such, this section discusses the role of Te Tiriti o Waitangi in this review. We then introduce Te Ao Māori and mātauranga Māori. Both Te Tiriti and mātauranga need to be included in regulatory and decision support tools for them to be fit-for-purpose for Māori.

3.1 TE TIRITI O WAITANGI – ITS ROLE IN THIS REVIEW

Aotearoa New Zealand is in a unique situation. The relationship between Government and Māori as the indigenous people is well-represented through a range of concepts, which arise primarily from Te Tiriti o Waitangi (The Treaty of Waitangi). The original Tiriti between the British Crown and Māori was first signed on 6 February 1840 at Waitangi in the Bay of Islands. Te Tiriti eventually gathered over 540 signatures from around the country prior to the British interests (represented by Captain William Hobson) proclaiming sovereignty over the North Island and South Island on 21 May 1840 on grounds of discovery. Whilst Te Tiriti is now considered a founding document, throughout the intervening years prior to the passing of the Treaty of Waitangi Act in 1975, Te Tiriti was seldom enacted.

In 1975 the group Te Rōpū Matakite, created by Māori leader Whina Cooper, led the Māori Land March. This movement was arguably Aotearoa New Zealand's most notable hikoi (journey) undertaken as a form of protest. The march started in Northland on 14 September, travelled the length of the North Island, and arrived in Wellington on 13 October that year. The core kaupapa (purpose) of the march was to protest continued land alienation and cultural loss. Te Tiriti o Waitangi had not achieved the desired outcomes for Māori. Land is, and will always be, the identity of the people, of all Māori. Land is also the driver for this review, hence the relevance of Māori interests in its outcome.

On 10 October 1975 The Treaty of Waitangi Act was passed and (including subsequent amendments) has in many ways contributed to a renaissance of Māori culture and identity. The Act recognises both Te Reo Māori and English versions of Te Tiriti. It established the Waitangi Tribunal as a permanent commission of inquiry to hear claims against the Crown by Māori. Later legislation began to refer to the 'Principles' of Te Tiriti, recognising that the *intent* of Te Tiriti has relevance in the present time, not the actual words (which were relevant in the early 1800s).

While most contemporary legislation refers to the Principles of Te Tiriti o Waitangi, the Principles lack any statutory definition and, so, are drawn from case law. There are many iterations of Tiriti principles, but the following represent the most identifiable interpretation:

- **Partnership** – Te Tiriti is essentially about a partnership between Māori and the Crown. This includes good faith and consultation. As with all partnerships, both partners need to benefit from the relationship.
- **The essential bargain** – This is drawn from Articles 1 and 2 of Te Tiriti. Māori ceded governance (Article 1) in return for the retention of resources for so long as they so wished (Article 2).
- **Rangatiratanga** – Te Tiriti guarantees rangatiratanga (self-determination) for Māori i.e. the ability to make informed choices that affect Māori themselves. This includes the interfaces between humans and resources.
- **Protection** – Article 3 of Te Tiriti guarantees for Māori all the rights and privileges which the Crown gave to its British subjects.
- **Consultation** – This is included as one of the principle rights drawn from Te Tiriti partnership. Consultation, however, does not have any single definition and is also interpreted through case law. Some fundamental components of consultation such as the process of communication between parties, parity of costs, expertise and timeliness are all factors which also contribute to good working relationships drawn from a partnership.

3.2 I TE TIMATANGA (IN THE BEGINNING)

For Māori the origin of the world as we know it is captured by mythology and whakapapa, a construct that allows us to view the world through a cultural lens that also defines Te Ao Māori (the Māori world) and that, in turn, informs cultural knowledge and behaviour.

In this mythology, there were three periods in which the universe was created. The first was *Te Kore* in all its various names; the vast emptiness. This was followed by *Te Pō* – again in all its names; the long night. Both these periods have no specified time period. The third period is *Te Ao Mārama*; the world of light in which we now live. Within *Te Pō*, the whakapapa culminates in the acknowledgement of a primeval being; Ranginui who later begat Papatūānuku from within himself and then took to be his wife (Broughton, 1979).

Ranginui is personified as ‘the Sky Father’ and Papatūānuku as ‘the Earth Mother’. Ranginui and Papatūānuku were responsible for darkness through their coupling and light through their separation. Ranginui and Papatūānuku produced 70 offspring. When they were finally separated the world of light became a reality. Papatūānuku said to her offspring that she would provide sustenance for them. From this beginning Māori continue to dig into the earth to gain their sustenance, primarily aruhe and kūmara, but also taewa and other crops.

Each child of Ranginui and Papatūānuku was assigned to a resource in nature. Their offspring then accounted for all other resources. An example is Tane’s union with Hine-tupari-maunga which resulted in Parawhenuamea, the parent of freshwater and whose son, Rakahore, became responsible for stones and rocks. Rongo-marae-roa (syn. Rongo-ma-Tane) and his brothers Tane-te-hokahoka and Tangai-waho were appointed as preservers and caretakers of the fertility and welfare of forests and plant life. Rongo-marae-roa held that status over all agriculture and cultivation (not of harvest, just the preceding activities) and with the practice of peacemaking and the expression of hospitality, generosity and manaaki tangata. Another brother Haumia-tiketike held the same status over uncultivated food and crops. Tane-muriwai controlled the fresh waters of the earth.

With reference to this review, it is Papatūānuku, the representation of the physical earth, to whom we are indebted. Papatūānuku provides for our sustenance and survival. We are wholly reliant on our ability to maintain the quality of the physical resources to achieve this. The ability to produce food crops, to forage for wild foods, to maintain a resource that sustains all other biology, to fish and to hunt, are all a consequence of our ability to maintain Papatūānuku. To achieve this, Māori have a responsibility known as kaitiakitanga to ensure we do not compromise the mauri (spirit) of our natural world. Kaitiaki are those persons charged with protecting Papatūānuku. They can draw from the broadest range of tools stemming from mātauranga (traditional knowledge) and the contemporary tools and technology that are constantly emerging. Overseer is one such tool which has the potential to support kaitiaki in their role as resource managers.

With a consensus across all tribes that whenua refers to land in general (aside from other meanings) the application of the word to the whole of the land resource is appropriate. For the purposes of this review, whenua is taken to refer to land in all its forms. The economic utility of whenua is based on the knowledge and utility of the physical soil resource. This must consider the emotional relationship between the people and the land, the tangata whenua, and how whakapapa assists Māori in acknowledging these emotions.

Darcy Nicholas (Te Ātiawa, Ngāiterangi, Taranaki) wrote of his understanding from an Ātiawa perspective of the association between the people and the whenua as:

> *‘Even though [they] are learning the Māori language, they forget that nothing dies in the Māori world. Things merely move through different dimensions – the flax, for instance, becomes a cloak of immense beauty. Those we love become part of the beautiful land around us. This is our bond with the land. It is our ancestor and as such, part and parcel of what we are. It has sustained the life of our people for hundreds of years…’* (Nicholas and Kaa, 1986, p. 32)

Returning to the economic aspect of land, the Waitangi Tribunal has stated that in 1840 each hapū had rangatiratanga over its whenua. Hapū were political units exercising autonomous resource management (Pond, 1997). As the economy of each hapū throughout Aotearoa New Zealand was different, hapū relied on varying resources to gain their livelihood: some marine, some forest, some cultivated crops, and so on.

3.3 HORO MAUNGA KI TUA, PĀKIRA KI TANGATA KOTAHI[9]

Like baldness, the beauty of a mountain slowly erodes away through slips.

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[9] Literally: ‘as a landslide denudes a mountain, so baldness comes to a person’. A whakatauki and metaphor illustrating the ability to see the links between actions that may, at first glance, seem remote.

The term Māori science is a misnomer, as it compares Māori knowledge and knowledge creation to that of other cultures. Science for Māori is a holistic concept. It still works with and creates knowledge but has a much wider dimension. In a traditional context, mātauranga Māori (Māori knowledge) was retained as an oral tradition supervised under tikanga (tribal or familial processes). In the present day, there are issues with maintaining oral tradition, through the competency of younger generations in applying traditional knowledge, and the conflict between different media by which knowledge is easily transmitted.

The major difference between mātauranga Māori and formalised approaches to science is the inclusion by Māori of a worldview based on spiritual origins in their understanding of knowledge. There are four dimensions within which Māori perceive themselves and all resources:

- Tinana – physical
- Wairua – spiritual
- Hinengaro – intellectual
- Whanaungatanga – social/cultural

It is, therefore, apparent that Māori science is more than just intellectual knowledge. It draws from the wider four dimensions and contributes to and carries other responsibilities, such as whakapapa (the continuation of people).

Professor Mason Durie argued that the relationship between mātauranga Māori and western science is one of the main contentious issues for scientists (Durie, 1996). The understanding that Māori views, beliefs, relationships and spirituality are bound together is holism. This forms the basis of Māori science. It is the joining of the past with the present, physical and metaphysical, people and the environment. Durie (1996) states that while these points may seem to highlight differences between the science practitioners, there are several striking similarities as well:

- The effects of unseen forces: for example, *tapu* in Māori science and various forces in physics such as gravity or torque;
- The processes of deduction used to reach conclusions; and
- The development of systems to retain and retrieve knowledge.

Marsden (1992) identified the religious, philosophical and metaphysical attitudes in Māori culture as contributors to understanding Māoritanga (and mātauranga) as a whole. He recognised that Māori values and attitudes are drawn from cultural experiences. While experiences lack objectivity and, therefore, academic recognition, objectivity is a form of abstraction or model and not the same as reality. Māori knowledge is a thing of experience and existence within a cultural milieu.

It is becoming increasingly clear that the polarisation of indigenous and scientific knowledge is untenable. There is a greater sympathy for the view that indigenous knowledge is complementary not competing, and that it represents a sense of additionality (Roskruge, 2007). While the importance of indigenous knowledge is receiving attention, most information about indigenous knowledge is oral patrimony from generation to generation and varies between tribes and regions. There is also prejudice in some quarters that indigenous knowledge is against development.

3.3.1 Farming systems

A key point to note about Māori before the arrival of Europeans is that they did not have access to livestock or their by-products (dung, urine etc.). These were often mainstays in the fertilisation of land for crop production by most other indigenous peoples. Māori tradition frowns on the use of waste products as manure on food production sites. Waste materials were returned to non-productive land areas to break down naturally and then re-incorporate into the soil profile. This returned the products to Papatūānuku who would purify them before they could contribute to any system accessible by her descendants (mankind), especially food production systems.

Modern farming systems in Aotearoa New Zealand are now based on animal husbandry as part of land-use rotation. They stem from the origins of agriculture. Māori did not have this aspect in their land management systems and thus relied on their own interpretation of soil fertility factors and the needs of crops.

Soil resources are constantly assessed for many and varied uses. There is constant pressure from the community to benefit from the use or development of soils. However, our demands are changing. It has become apparent that we need to work with soil quality factors as we recognise that sustainable management means more than just erosion control. It is important to align soil resources to other environmental factors such as weather, climate change and land-use activities. The Māori land resource is possibly the largest untapped resource in Aotearoa New Zealand's primary sector. It can contribute to future national and Māori economic development. However, the cultural aspect of the landowner's relationship to the resource must be recognised and respected for them to want to develop the land or change their management.

Cultural indicators for Māori land resources are not just soil- or crop-specific. It is important to acknowledge the relationship and the mātauranga that has developed as a result. Cultural indicators, therefore, build on unique Māori relationships with the land resource and contribute to the quality and knowledge of the resource overall. Expressions of values and cultural factors such as mauri and whakapapa define the Māori knowledge around the land resource.

In some instances, mātauranga merely informs the scientific community rather than integrates with it. It is important for Māori, especially in the context of rangatiratanga, that mātauranga Māori makes a positive contribution to science, especially to disciplines with which there are obvious affinities such as agriculture, horticulture and pedology. Therefore, mātauranga Māori is better represented through processes that encourage integration.

3.4 THE PRESENT

In our modern world natural resources are viewed through a generally reductionist scientific lens. This contradicts the holistic indigenous view of them, which often associates the resource with an ancestor. This ensures the relationship of any physical resource with humanity is built on respect and recognises the contribution of each to the other's endurance and survival. This applies to the Māori understanding of the soil and water as elements aligned to Papatūānuku, and thereby the provider of rudiments necessary for survival. The Māori relationship with natural resources is, therefore, both primal and physical. Any effect on the soil or water – positive or negative – will have a flow-on effect to the people who rely on it.

Colonisation introduced an array of exotic flora, fauna and land-uses that have seriously affected Papatūānuku in many ways. Most important for a country whose economy is driven by the primary sector, farming systems have introduced new ecosystems, plant-based production systems, and relationships between people and natural resources. For Māori, this has meant a shift in land-use from a relatively benign system, centred on wild and cultivated harvests supported by extensive rotation periods for access and utility. Now there is an extensive pastoral approach that has no direct link to traditional indigenous systems. What effect has this change in land-use had on native and endemic biology? This question is largely unexplored. Contemporary issues (e.g., nutrient pressures, soil integrity, climate change) are becoming more apparent, as are issues of Māori food sovereignty. This is defined by indigenous peoples in the Declaration of Nyeleni (2007)[10]:

> *Food sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts the aspirations and needs of those who produce, distribute and consume food at the heart of food systems and policies rather than the demands of markets and corporations. It defends the interests and inclusion of the next generation. It offers a strategy to resist and dismantle the current corporate trade and food regime, and directions for food, farming, pastoral and fisheries systems determined by local producers and users. Food sovereignty prioritises local and national economies and markets and empowers peasant and family farmer-driven agriculture, artisanal - fishing, pastoralist-led grazing, and food production, distribution and consumption based on environmental, social and economic sustainability. Food sovereignty promotes transparent trade that guarantees just incomes to all peoples as well as the rights of consumers to control their food and nutrition. It ensures that the rights to use and manage lands, territories, waters, seeds, livestock and biodiversity are in the hands of those of us who produce food.*

This definition states the ambition held by Māori and other cultural interests and reminds us that ecologically sound and sustainable methods are imperative to achieving it. With pressures like climate change on land managers, it is important to recognise the array of tools and technologies which can

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[10] see https://nyeleni.org/spip.php?article290

support food sovereignty. The recent evolution of climate smart agriculture is one example of how traditional and contemporary knowledge bases can come together to achieve mutually beneficial desired outcomes. Technology inputs, such as models for improved production systems and soil management needs, are an important opportunity for Māori to work towards gaining food sovereignty from a cultural basis, and the security for future generations to continue to harvest foods from our natural resources.

Wai (water) – both surface and subsurface – is a finite resource that affects all other biological communities within our environment. Decisions concerning it need to reflect this and the importance of its sustainability for future generations. In economic terms, water is often referred to as the ‘fugitive resource’; it is dynamic and flows and meanders, creating relationships between the diverse parties that use it. Interdependencies between aspects of the water resource and users represent economic ‘externalities’ that are often not recognised by market processes. In Māori terms, it is recognised as ki uta ki tai, a life-giving element that flows from the source (the mountains) to the sea and draws from associated catchments to contribute to our wellbeing. We all must balance the social and economic demands on our resources. This does not diminish our role as managers of those resources. Māori have an enduring relationship with wai and all the life systems that depend on it. Through this relationship, there is recognition that the human community must survive and sustain the resource to ensure continuation of the community.

Overseer is seen as a tool to regulate nutrient inputs to land based on the knowledge that these inputs will progressively move through the soil profile to our wai. Papatūānuku is both the parent and protector of our natural world, including wai, and oversees the process of water filtration through the soil profile. The cultural value of the water resource, before any economic activity is applied, must be quantified through the estimated availability and quality of water from all sources. This includes surface water, groundwater, and the interchange between them, as well as the effect of climate on them. It is not unreasonable, therefore, to expect any decision-making process affecting the water resource (such as Overseer) to consider all water sources and their finite nature.

Applying an economic value to water is not easy. Water is a finite resource and is essentially the giver of life. It is difficult to quantify these statements economically, but it is common practice to apply a monetary value to water resources based on their contribution to industry or society and the accepted available volumes of the resource itself. Economically, water has a range of uses. Some are *in situ*, including cultural and aesthetic values such as hunting, fishing, swimming, and canoeing. Other economic uses of water require the displacement of the resource to support external activities (*ex situ*) such as horticulture, agriculture, hydroelectric power production, waste and effluent disposal, and industry. Arguably the economic value placed on water for human consumption (i.e. drinking, washing, cooking) is a separate economic application to the resource, and one which is hardest to place a value on because without it, we put our survival at risk.

From a Māori perspective, the quality of wai is measured through its mauri. This then defines the potential use of the wai including:

- wai-tapu of sacred origin;
- wai-pure for religious ceremonies;
- wai-tangata for everyday use; or
- wai-mate for water no longer able to sustain life forms.

Understanding the application of mauri by resource managers requires an intimate knowledge of the factors that impinge on the resource, both positive and negative, and the tools resource managers can utilise.

In Aotearoa New Zealand the water resource is, effectively, nationalised with Crown oversight and a range of statutory controls. This should reflect the relationship between the Crown and Māori encapsulated in Te Tiriti o Waitangi. Putting aside cultural factors, there are a range of technical factors affecting contemporary access and use of water. As iwi and hapū are not generally experts in this area they expect compliance mechanisms to help address their concerns. These concerns mostly relate to the mauri of natural resources, including water, soil, ecosystems under management, and climate. This can be expanded to include the use of tools such as Overseer, which are used in the regulation of inputs to production systems. How does Overseer interpret the expectation by Māori that water determinants will consider cultural drivers such as whakapapa and kaitiakitanga, and most importantly, contribute to maintaining the mauri of the resource?

The opportunity to participate in the management of natural resources, especially wai, is important to Māori. As kaitiaki, Māori input into resource management is necessary to ensure the survival of resources for future generations and their rangatiratanga. In this respect, rangatiratanga is the ability of Māori to be involved in the decision-making process on matters affecting them. By participating in regional planning, policy, and implementation, kaitiaki will meet their obligations.

Management needs to be proactive, not reactive. Iwi Māori participate in management as tangata whenua and have a wealth of local knowledge of their region and all resources within it – aspects that can only be of benefit to future decisions. They also carry cultural knowledge and mātauranga Māori, which means they bring a unique contribution to the processes that affect the future of water resources and help work towards positive outcomes.

3.5 CONCLUSION

Two key points are raised in this chapter: the definitive relationship that Māori have with the natural world, and the role of Te Tiriti o Waitangi and related principles in land and water decision support tools. The relationship of Māori to our natural world is determined through whakapapa and remains key to environmental management including of soil and water resources, especially in production systems. This relationship forms the foundation of mātauranga, which, in turn, informs cultural decision systems. Mātauranga is primarily applied through kaitiaki responsibilities so that resource sustainability is both understood and achieved. Both mātauranga Māori and the principles of Te Tiriti o Waitangi must be given effect in regulatory and decision support tools for them to be fit-for-purpose for Māori. This is best done through partnership. Building relationships between Māori, Government, regulators, and tool developers ensures consultation, collaboration, and mutually beneficial processes and outcomes.

4 Introduction to modelling

Nutrients lost from a farm are part of the landscape's overall nutrient balance. This balance involves imported and exported nutrients, changes in soil organic matter, and fluxes to and from the atmosphere. Nutrients can be imported directly through fertiliser, indirectly through animal feed, and some atmospheric deposition (usually quite small). An additional source of nitrogen is through atmospheric nitrogen fixation, for example by legumes. Nutrients are exported directly in products (crop yields, milk, meat, livestock, etc.). Losses of nutrients are primarily through leaching and runoff, and, for nitrogen, atmospheric losses as a result of ammonium volatilisation and nitrate denitrification. Nutrient losses through leaching and runoff are the diffuse sources of nutrient pollution to freshwater systems from farms. They are difficult to measure so models provide a means of attempting to quantify these losses. These losses are closely related to climate, farm management, and soil characteristics; so, even if specific measurements were available, it would be difficult to extrapolate them beyond the conditions under which the data were collected. Models, therefore, have great potential to help understand and quantify the complex interactions involved in farm and catchment nutrient dynamics.

Before considering Overseer in detail, we first introduce types of models and model evaluation which will put our review in context.

4.1 TYPES OF MODELS

Different types of models are described in the PCE's report (PCE, 2018), but we shall also provide a brief overview here; for more detailed discussions see Thornley and Johnson (2000), Thornley and France (2007). As mentioned by the PCE (2018), models are typically broadly categorised as:

- Empirical or mechanistic;
- Deterministic or stochastic; and
- Dynamic or steady state.

These are considered in turn.

4.1.1 Empirical and mechanistic models

Models tend to have both empirical and mechanistic components and exist on a continuum from more empirical to more mechanistic. Empirical models are essentially equations that are fitted to data, while mechanistic models, as the name implies, are based on our understanding of the underlying mechanisms driving system behaviour.

As an example, consider an experiment to observe the growth of a cow from birth to maturity and suppose that the weight is measured every week for around two years. This will give a detailed impression of growth with about 100 data points. It may be convenient to analyse the data by fitting a sensible growth curve to the data, which can summarise the 100 data points. This curve may have three or four parameters and provides a useful framework to analyse the data. This is an empirical modelling analysis of the data. Empirical models can be a powerful tool in analysing data, but care must be taken not to extrapolate the analysis beyond the conditions under which the data were collected. For example, if the experiment measured the weight of cows living in barns exclusively eating grain, the curve would not help us understand the growth of pasture-raised cows. Of course, this type of empirical modelling can be applied to most experimental programs. Another example might be a nitrogen fertiliser response curve where crop yield is carefully monitored under different fertiliser regimes. An empirical modelling analysis may involve fitting a curve to the data relating crop yield to applied nitrogen, but it will only apply to the particular weather conditions of the experiment, soil type, and other factors such as application or availability of other nutrients.

Empirical models are, therefore, essentially direct descriptions of observational data and can be exceedingly useful. The approach is primarily one of examining the data, deciding on an equation or set of equations, and fitting these to the data. Essentially, an empirical model re-represents the data, perhaps more conveniently, and no new information is acquired. The primary and essential constraint on the use of empirical models is that they must not be extrapolated beyond the range of conditions under which the data used in derivation were collected.

Mechanistic models are based on our understanding of the underlying mechanisms involved in system behaviour. Mechanistic models can vary in degree of complexity, and the choice of model structure generally reflects the focus of the study driving model development. Returning to the example of the cow growth data, a mechanistic model may incorporate metabolic processes as they are affected by diet. This will require careful monitoring not only of animal weight gain, but also diet quality, physiological responses after feed consumption, accretion and breakdown of muscle, fat, and bone tissues, etc. Based on our understanding of animal growth and metabolism, the model might include the energetic and nutrient costs associated with fat, muscle and bone synthesis, as well as other process (e.g., maintenance of existing body composition, costs of moving around the paddock, etc.). This will require an understanding of feed digestibility and how digestible feed is converted to metabolisable energy (ME) (energy available to the animal for physiological processes). Building a mechanistic model of cow growth will therefore involve a mathematical description of the physiology of growth and metabolism based on current understanding. However, to verify the model behaviours as generally applicable for a range of growth conditions (e.g., across feeding scenarios or animals with different genetics), it will be necessary to test the model behaviour against a range of experimental data (see 4.2).

A major advantage of mechanistic models over their empirical counterparts is that they are designed to be used to analyse system behaviour beyond specific experimental conditions. To ensure greater confidence in model predictions outside of known ranges, mechanistic models usually adhere to first principles, such as conservation of mass and energy, to ground model predictions within the biophysically feasible range. Consider again the example of crop response to fertiliser. Suppose we restrict attention to available nitrogen and climate variation and assume that other nutrients are non-limiting and that pests are controlled. While this imposes some limitations on the model, it is much broader than the simple empirical response. The key climatic factors affecting growth are:

- light, which is the source of energy for photosynthesis;
- temperature, since most biochemical reactions are temperature dependent (e.g. Johnson and Thornley, 1985);
- rainfall, which has a direct effect on available soil water;
- vapour pressure deficit (related to relative humidity) which, along with the net radiation balance and temperature, has a direct effect on plant transpiration and soil evaporation.

Since we are also interested in the response to nitrogen, it is necessary to define the soil nitrogen that is available to plants. This requires us to model the soil nitrogen cycle (this involves various processes discussed in Chapter 8). Different system components are closely related. For example, nitrogen transport both through the soil profile and across the surface is directly influenced by soil water dynamics, so these dynamics must also be incorporated into the model. Once we have this crop growth model, we can analyse growth under conditions for which there may not be specific experimental observations. For example, climate variability is a fact of life and rainfall patterns are rarely, if ever, repeated. If we have confidence in the model description of water and nutrient movement in the soil and their influence on plant growth, we can use the model to study crop growth using historical climate data, and possible future projections. This may give valuable information into factors such as risk associated with periods when runoff or leaching are most likely to occur.

While there is an appeal to the simpler concept of empirical modelling, for complex agricultural (and other) systems it is not current feasible to collect sufficient data to represent all possible combinations of circumstances such as soil type, climate, or management. Conversely, mechanistic models can be used to explore multiple scenarios. However, these models should be tested both for internal consistency and against experimental data – this is discussed in 4.2. For more discussion on types of models see, for example, Thornley and Johnson (2000) or Thornley and France (2007).

4.1.2 Deterministic and stochastic models

Models can also be separated into deterministic or stochastic in nature. In its simplest form, a deterministic model may be one that has a single solution for given conditions, while stochastic models include variable system behaviour.

As an example, consider a deterministic model of animal growth under grazing. A deterministic model may assume that all the grazing animals are identical, will have the same intake demand, and will graze the same amount of pasture. They will then grow at the same rate. On the other hand, a stochastic model may simulate genetic and behavioural variability in the animals, so that they have different intake demands and will eat different amounts. Taking this a step further, the animals may select different areas of the pasture to graze so that the pasture is not a perfectly even homogeneous distribution of identical plants but has patches. Continuing this vein, dung and urine returns will not be evenly spaced across the pasture, resulting in different distributions of nutrients, which will then further cause variation in growth across the pasture. In these examples, in order to include stochasticity, it is necessary to introduce some form of randomness to define the processes that cannot be predicted (e.g., precisely where the animals graze, where dung and urine are deposited, etc.). Stochastic modelling is discussed further below in the context of climate variability (see 4.2.5).

Although deterministic models may seem precisely defined, this does not necessarily mean that they are always entirely predictable. Perhaps the most celebrated case where this is not the case is the so-called 'butterfly-effect', a term first coined by a climate scientist Edward Lorenz. Lorenz found that extremely small changes in the initial conditions in the computer program of a climate model he was working with led to completely different results. This led Lorenz to conclude that small perturbations in climate systems can have a dramatic effect on subsequent model and system behaviour (Lorenz, 1972). Lorenz paraphrased this as a butterfly flapping its wing in Brazil potentially causing a tornado in Texas. For climate models, this may imply that small changes in initial conditions may affect whether the model predicts extreme events such as tornados. We are all familiar with this concept through the everyday challenges we see faced by weather forecasts that may not always give us a perfect indication as to whether we should go to the beach next weekend. This applies beyond climate simulation models. Simulation models of natural ecosystems also face this type of instability. For example, it is virtually impossible to give a precise prediction of the growth of multiple plant species and their relative distribution in the ecosystem.

4.1.3 Dynamic and steady state

As the names imply, a dynamic model is likely to be continually changing whereas a steady state model will be in some form of equilibrium (e.g., outputs from the system being the same as inputs to it). In general, a pasture or crop system will be dynamic, as plant growth depends on variation in climatic factors (e.g., solar radiation, temperature) as well as management factors. An approximate steady state may occur, for example, with mature sheep grown primarily for wool. Provided they are adequately fed, their weights may stay relatively stable throughout the year and from year to year. While it is sometimes helpful to consider systems in steady state, it should not be at the expense of important dynamic variability that may capture useful information.

4.2 MODEL STRUCTURE, TESTING AND EVALUATION

An essential part of model development is ensuring that the model structure is adequate for the intended objectives of its use. This should be an on-going part of the model development. It is common to view the primary process of testing and evaluating the model as being a comparison with experimental data, but there are other aspects involved that are equally important.

Ensuring that the model structure is appropriate perhaps lies at the heart of model development. As an example, a paper aeroplane is a model of the dynamics of flight. If we are trying to establish a relationship between glide distance and wing surface area, a paper aeroplane might be an adequate experimental model. By comparison, if we are attempting to improve wing design and safety for passenger jet engines, most airline passengers would likely prefer if paper aeroplanes were not the experimental model used for design improvements. While perhaps seeming trivial, the example illustrates the importance of considering the application context when evaluating model adequacy. Paper aeroplanes do not have independent thrust, and there are few who would suggest they represent a sound basis to describe a commercial passenger aircraft. Although quite straightforward in this example, assessing the adequacy of models for their intended purpose is not always simple.

Most assessments of model adequacy (e.g., Oreskes *et al*., 1994; Thornley and Johnson, 2000; Thornley and France, 2007) focus on the following five critical valuation criteria:

1. Model structure: does the model structure suit the objectives of the intended model application?
2. Data used in model development: are the data used to inform the model structure appropriate and adequate?
3. Model behaviour: does the model provide sensible and robust outputs?
4. Model sensitivity: how sensitive is the model to variation in input parameters and driving variables, such as climate, and is the sensitivity realistic?
5. Agreement with experimental data: does the model give good agreement with appropriate available experimental data?

Collectively, these criteria inform the confidence we might have with the model simulation results. As with all models, there will be uncertainty associated with these results. Uncertainty can come from the model structure itself, as well as limitations in data used to inform or test the model. The points listed here are considered in turn.

4.2.1 Model structure

When defining model structure, often people think only of the broad classifications described in 4.1. However, selection of model structure is critically important irrespective of the classification of the model. For example, model structure is just an important a consideration for more empirical models as it is for more mechanistic models. Models are representations of the real world and are used when real-world measurements or observations are imprecise, impractical, expensive, or otherwise infeasible. This can include projections into the future to explore impacts of climate variability or climate change. As such, the definition of a model implies it must be informed by real-world processes. It is widely accepted as best-practice within modelling investigations to retain consistency with underlying physical and chemical laws governing the system of interest. These can include basic principles such as mass conservation, or energy dynamics and universal gas laws involved in the evaporation of water from soil or transpiration from the leaves. In the case of mechanistic models, this often means defining the pools and fluxes within the model to follow these underlying rules. In the case of empirical models, adherence to basic principles can be accomplished through careful selection of equation structure and allowable parameter ranges (e.g., asymptotes, allowable growth rates, etc.). Tenets of good model structure transcend model classifications. The evaluation of the structural adequacy of any model class can focus on three questions:

- Is the structure of the model (inputs, relationships, outputs) sufficient to describe the biological, chemical, or physical relationships needed to accomplish the end use?
- Does the structure of the model self-protect against out-of-range predictions?
- What type of output uses (prediction, scenario comparison, optimisation, etc.) are supported by the model structure?

If critical biological, chemical, or physical relationships are not represented, poorly represented, or inaccurately represented within the model, this constitutes inadequate model structure and is a major barrier to most end-users.

If the model structure does not rely on conservation of mass and energy or other self-protecting structures, use for prediction in situations outside the scope of the model training data or outside the model parameterisation conditions should be discouraged.

If the model structure does not suit the mechanism of use (e.g., inadequate for optimisation, but optimisation is a goal of end-use), the physical structure of the model should be re-evaluated. Sometimes this re-evaluation can result in the same model structure being of value, but within a different context.

4.2.2 Data used in model development

Models have inherent relationships derived from experimental or observational data. Assessment of the adequacy of data used to inform model predictions is of paramount importance. Like assessment of model structure, evaluation of data used in development is equally important across model classifications. As discussed in 4.1.1, empirical models are used to synthesise data and cannot be used outside the range of the derivation data. To a certain extent, the same caveat exists for mechanistic models, though the application constraint applies differently. In complex mechanistic models, the mechanism-driven structure is typically designed to protect against out-of-range predictions from the relationships encapsulated within the model, and derivation data are typically used only to specify individual parameters or occasionally define relationships. Because of these structural differences in the way data are used in constructing mechanistic and empirical models, mechanistic models are typically suitable for predictions across the range of scenarios cumulatively described by the model structural relationships and by the derivation data. For example, a sound biophysical model of plant growth that incorporates responses to climate inputs can be used, with sensible caution, to explore possible responses to climate change because this model relies on the types of self-protecting structures mentioned above. However, such a model may be inadequate for exploring how novel crop genetic varieties may respond to climate change. In that case, additional data may be required to parameterise the novel crop.

4.2.3 Model behaviour

Assessing model behaviour is a vital step in model development and assessment, and this goes beyond comparison with experimental data. Although perhaps seen as a qualitative process, evaluation by experts and scientists with an understanding of the system being modelled can reveal missing relationships within models, contextualise model feedback loops, and confirm the appropriateness of general model behaviour. This type of model assessment is broad and far-reaching and is to be viewed in the context of attempting to find flaws and limitations in the model rather than looking to confirm the existing model structure is adequate for all purposes.

4.2.4 Model sensitivity

An essential aspect of model evaluation is determining the sensitivity of model predictions to variations in input. This process can help to contextualise the relative implications of errors in model input and can help inform whether the model behaviours align with expert expectations. Sensitivity analysis is commonly conducted one variable at a time by varying the input and evaluating the change in the output. There are numerous scaling and indexing approaches that can subsequently be applied to understand the relative sensitivity of input. Within biological and ecological contexts, unilateral assessments of sensitivity are often inappropriate and can lead to severe over- or under-estimations of sensitivity because of inherent covariation in input parameters. In response to this challenge, several approaches to global sensitivity analysis have been developed to contextualise the relative sensitivity of inputs better while accounting for this covariation. In general, conducting both these types of analyses can be useful for understanding and querying the behaviour of the model.

4.2.5 Comparison with experimental data

Perhaps the most widely discussed area of model assessment is comparison with experimental data. However, this part of the model development process is best addressed after the previous aspects have been explored. Regardless of how closely the model may fit a dataset, if it has been demonstrated to lack the versatility and robustness to reflect broader system behaviour, then agreeing with one dataset is largely irrelevant.

The limitations of comparison with experimental data – An example

Repeated agreement with experimental data may be of limited value unless every effort is made to obtain the data under a wide range of circumstances. Take, for example, experiments to establish the boiling point of water. An experiment to measure this in Wellington could be repeated many times and provide convincing evidence that pure water boils at 100°C. However, it would only take one similar experiment at the top of Aoraki/Mount Cook in the Southern Alps to show that this is not universally true. In fact, with the height of this mountain reported as 3,724m, pure water will boil at around 87°C owing to the decline in atmospheric pressure at altitude. Thus, once this has been demonstrated it informs further model development to incorporate effects of atmospheric pressure. (The theory for this particular scenario is, of course, well-established.)

Agricultural systems are complex and, as highlighted above, involve the integration of many processes such as: plant photosynthesis, growth and development; soil water and nutrient dynamics; and, for pasture systems, animal intake, metabolism and growth. Often, model testing is restricted to whole-system behaviour. If the model and data agree, then some level of 'validation' is said to have been achieved. However, if they disagree, then the usual conclusion is that the model is at fault and either the structure requires revision or parameters need adjusting. However, any model of a natural system is an approximation, and can never incorporate all factors affecting system behaviour. When we analyse the data, the same caveat applies – we do not know, and cannot measure, all the factors affecting system behaviour and, therefore, we do not know, and cannot measure, the uncertainty in the data (Oreskes *et al*., 1994). So, unless we can be sure that all the factors affecting the data are incorporated in the model, we cannot conclude that when they agree we have validated the model and when they do not fit we cannot conclude we have proved the model to be false. This does then beg the question of how we test and evaluate models – it involves a careful investigation into both the data and model with a view to seeing how each can inform the other.

As we have mentioned, a sound mechanistic, process-based model allows the model structure to be closely scrutinised in terms of its underlying structure and not just its overall behaviour. Then, overall system behaviour can be explored under a wide range of circumstances that are far beyond the scope of any practical experimental observations. Examining model behaviour in this way is vital in helping improve its robustness and applicability. Once the structure is identified as appropriate or adequate, the model can be compared with relevant data. It is obviously a desirable outcome that they agree but, when this does occur, careful evaluation of the structure of the disagreements between the model and the data can help inform on how severe the disagreements are. As described in 4.2.5.1, some types of disagreements are less concerning than others. When, as is inevitable, the model and data do not agree, this provides an opportunity to examine aspects of the data, model setup and underlying model structure.

It is well recognised that data collection has its challenges. When there are discrepancies between model and data, there is value in scrutinising the data as well as the model. For example, with a climate driven model, the climate data used should reflect the actual climate conditions for the period when, or at the location where, the data were collected. Measurements of system variables also pose challenges. For example, measuring pasture dry weight can be difficult owing to pasture heterogeneity. Similarly, critical soil physical characteristics can vary considerably over relatively small areas. Recognising the areas where there is data uncertainty can help contextualise measurements of model uncertainty and can provide a clearer picture of whether model structural improvements are required.

4.2.5.1 Model accuracy and precision

In situations where data are predominantly appropriate for model evaluation, agreement between model predictions and experimental data is often discussed in terms of precision and accuracy. Accuracy defines the closeness of model-predicted values to true values, on average, i.e. whether a model can predict the correct value. A model with poor accuracy can also be described as biased, because, on average, it will tend to under- or over-estimate the true value. Precision measures how close individual model predictions are to one another. Precision can also be described as how consistently the model predicts similar values. Quantitative values are often used to objectively define the accuracy and precision of a model. Statistics like concordance correlation coefficients define accuracy, and the coefficient of determination can be used to describe precision. Appropriate cut-offs for these statistics are widely debated in the literature, undoubtedly context- and dataset-specific, and definition of such cut-offs in this context is outside the scope of this review. The concepts of accuracy and precision are often described using the classical target image (Figure 4.1), which highlights how model predictions can be accurate without being precise, and vice versa.

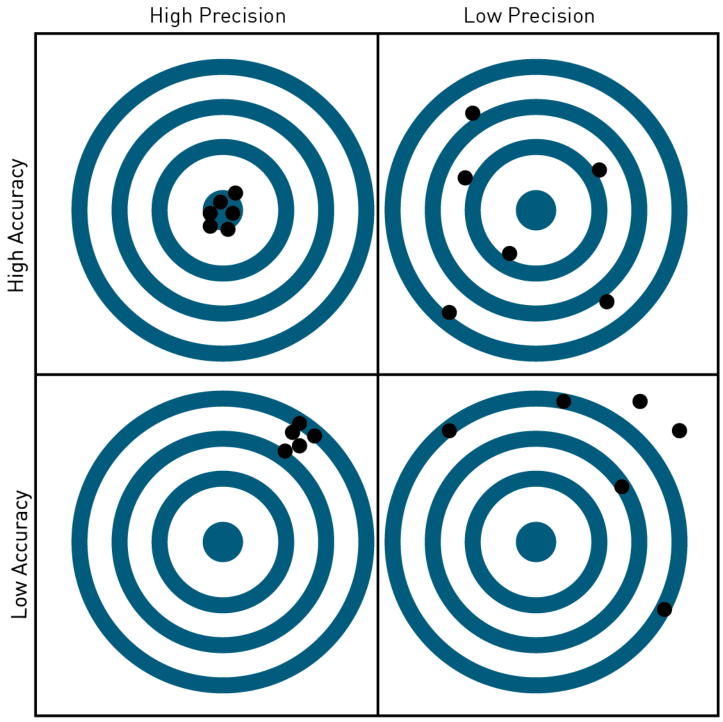

Figure 4.1 Model accuracy and precision

In the case of complex biophysical systems, assessments of model precision and accuracy often focus exclusively on the final output metric, for example the nitrogen loss from a field. However, uncertainty in model predictions will aggregate throughout successive calculations internal to the model structure. This propagation of error should be considered in a proper assessment of model adequacy. To understand the importance of characterising prediction errors, consider a pasture growth model incorporating responses to climate, soil water and nitrogen dynamics, and plant tissue dynamics and senescence. Assume that we have 20% error in predicting soil water dynamics,15% error in prediction soil nitrogen concentrations, 10% error in predicting root mass, and 15% error in predicting senescence. You might look at the error in predicting senescence and find confidence in the model's predictive capacity because the error is only 15%. However, when you factor in the uncertainty surrounding prediction of photosynthesis (20%) and root mass (10%) the error could be even higher (depending on whether there is any correlation between the prediction errors, and on the nature of the relationships between photosynthesis, root mass, and senescence). The interpretation of model goodness of fit may differ tremendously between whether the error is estimated at the bottom or top end of that range.

Another major implication of the precision and accuracy of a model is associated with the idea of predicting changes or responses, rather than predicting absolute values. Commonly, modellers and model users advocate using a model to understand relative differences rather than absolute values. This is because the perceived accuracy requirements surrounding the prediction of relative differences are more lenient than those associated with the prediction of absolute values. To predict an absolute value, a model must be both precise and accurate. To predict a relative value, any mean bias in prediction will average out, therefore relativistic usages can tolerate high mean bias in model estimates.

Figure 4.2 shows three critical example scenarios with different types of prediction errors. In all scenarios the circles represent the intersection of observed and predicted values for individual data points within a six-point dataset. The black dashed line represents the line of unity (the line where observed and predicted values are equivalent, on average). The red dashed line shows the best fit through the data (the true association between modelled and measured data).

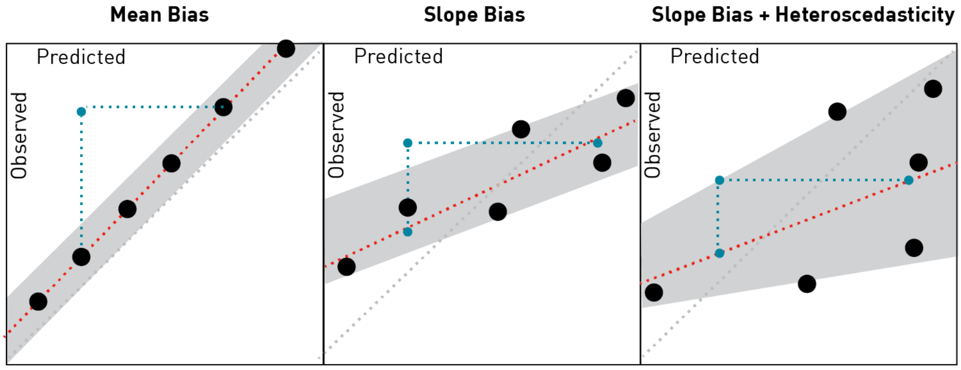

Figure 4.2 Types of prediction error

To predict absolute values correctly, the model predictions must lay as close to the line of unity as possible. However, it is quite common when evaluating models against new datasets to have the mean prediction differ from the mean of the dataset (i.e. **mean bias**). In this case, the model may not adequately predict the absolute value (red line differs from the black line); however, it is still possible to predict the relative association among points accurately. This is shown by the solid and dashed blue lines in Figure 4.2, which represent the true (solid) and modelled (dash) differences predicted between two example points. In the scenario where mean bias exists in model predictions, using relative changes in model outputs can overcome the prediction error limitation. Unfortunately, this is only true in practically perfect scenarios.

In many cases, the model predictions will exhibit **slope bias**, meaning that the higher values are consistently over- (or in some cases under-) predicted. This scenario is shown in the second panel, where the observations at the lower end of the data result in observed values that are greater than would be expected, while the opposite trend exists at the upper end of the data. In this case, we can see the true distance expected between the two points is much smaller than the predicted distance. In practical terms, we would over-predict the response associated with moving from point 1 to point 2. This slope bias can occur with respect to predicted values or to other variables. In either case, the model might predict a 10-unit change, but the true expected change may be five units. If the magnitude of the change in prediction does not matter, models with slope bias can be appropriate for generating relative predictions. However, we find it challenging to conceive of such a scenario because the questions of "*what is a minimal predicted change to have confidence a true improvement is realised?"* will always loom.

The final scenario is unfortunately the most common when evaluating biophysical models due to the type of data collected in these systems and the challenges in appropriately modelling complex systems. In this scenario, there is both slope bias and heteroscedasticity. Heteroscedasticity is the condition where the uncertainty in prediction scales with the magnitude of the prediction. In this case, the aforementioned issues with slope bias are exacerbated by the fact that our confidence in comparing the average model prediction to the average observation differs across the scope of prediction. In Figure 4.2, at low predicted values our relationship is fairly consistent. However, the higher the prediction, the less certain the association between observed and predicted values becomes. This shift in understanding of the strength of association between observed and predicted values is highlighted in the grey tone. At the extreme upper end of the plot, the association and predicted values could be anything from observed being less than half of predicted through observed equalling predicted. This means that not only does the model over-predict the relative change between two points on average, but we also have greater uncertainty surrounding how severe the over-prediction is because the uncertainty in prediction at the lower point is less than it is at the upper point.

4.2.6 Summary

To summarise, model evaluation techniques transcend model classifications. Irrespective of the confidence in the model or its history of use, we should continually be testing and evaluating model structure and behaviour to ensure models continue to match our constant updating understanding of complex natural systems. It is self-evident that no biophysical ecosystem model can ever be complete and on-going development should be a key part of any modelling project. This may involve abandoning aspects of a model as well as incorporating new features or refinements. Working with observational data is a vital part of the testing process, but the data observations and the factors affecting those observations must also be open to scrutiny. In addition, effort should be made to obtain or derive experimental data for a wide range of circumstances and conditions. For example, when modelling nitrate leaching, it is essential that data are obtained for as broad a spectrum of different soil types and landscape contours as possible. Certainly, demonstrating a good fit to limited, or similar, data should not be seen as conclusive evidence that the model is universally accurate.

The notion of testing and evaluating models has occupied scientists and philosophers for centuries. It is beyond the scope of this document to go into detail, but further background can be found, for example, in Oreskes *et al*. (1994), Thornley and Johnson (2000), and Thornley and France (2007). One common theme from all of this work is that claiming a model has been validated when comparing it with experimental data is not appropriate. It is a failed attempt to falsify the model. The more this is done, the more confidence there can be with the model. (It is also perhaps worth noting that other branches of science tend not to use the term ‘model validation’ but say that the model explains the data.) Therefore, while comparison with experimental data can increase our confidence in the model, we cannot be sure that a model is adequate without first assessing its structure, underlying data, behaviour, and sensitivity.

4.3 MĀTAURANGA MĀORI

Mātauranga Māori provides another useful lens through which to evaluate models in Aotearoa New Zealand. In the context of environmental models, the key question is whether they support kaitiaki to improve or sustain the mauri and mana of Papatūānuku (see Chapter 3). One way to assess the mauri and mana of Papatūānuku is through te whare tapa whā (the four cornerstones of Māori health). This framework is usually applied to human health (e.g., Ministry of Health, 2017) but Papatūānuku is personified as the Earth Mother so the application to environmental health is appropriate.

The walls of the whare (house) symbolise the four dimensions of health and the whare’s connection to the whenua forms the foundations for the four dimensions. The four walls are taha tinana (physical wellbeing), taha wairua (spiritual wellbeing), taha whānau (family wellbeing) and taha hinengaro (mental wellbeing) (Durie, 1994). In the context of human health, we might ask the following questions:

- **Taha tinana**: what is the capacity for physical growth and development?
- **Taha wairua**: what is the capacity for faith and wider communication? Spiritual essence determines who and what we are, where we have come from and where we are going.
- **Taha whānau**: what is the capacity to belong, to care and to share as part of wider social systems?
- **Taha hinengaro**: what is the capacity to communicate, think and feel?

These align with the four dimensions from which mātauranga Māori draws (see 3.3). Environmental models should support kaitiaki to uphold taha tinana, taha wairua, taha whanau, and taha hinengaro of Papatūānuku. In this context, we could ask:

- **Taha tinana**: Does the model show the physical state of Papatūānuku? Can it provide an understanding of how the physical state of Papatūānuku could be further developed or improved? How accurate are model estimates? Do they allow for investigation of possible mitigations?
- **Taha wairua**: Does the model provide an understanding of the state of Papatūānuku in the past? Can it help kaitiaki investigate possible futures? Does the model have the capacity to compare scenarios? Can it investigate future possible climates and inform climate change adaptation?
- **Taha whānau**: Does the model illustrate how Papatūānuku fits in with the wider system? Does the model include other dimensions of wellbeing, such as farm economics? Does it link well with other available tools to provide a wider picture?
- **Taha hinengaro**: Does the model help kaitiaki understand Papatūānuku's resilience? Does the model develop the intelligence of kaitiaki to future-proof their roles?

There is considerable work to be done by the wider science system in Aotearoa New Zealand to include Māori values in emerging technology. Therefore, a working relationship with Māori during new research and development is valuable.

4.4 SOFTWARE, TRUST AND TRANSPARENCY

To be useful as regulatory tools, mathematical models must be implemented as software products that are designed to be available to, and used by, a broad community beyond the original model developers. This context imposes different requirements on model developers compared with development and use of a model in a research context (Moore *et al*., 2014). These requirements include two aspects; the communication of the science in the model and assurance about the quality of the software implementation. These two aspects overlap. For example, communication of the science in a model is traditionally achieved by clearly and comprehensively describing (documenting) the choice and implementation of the equations included in the model. To provide assurance in the software, it is also necessary for the user to have confidence that the equations are accurately executed in the software code. Providing such confidence is often achieved by making the source code publicly available, as exemplified by the two most widely used agricultural systems models APSIM (www.apsim.info) and Decision Support System for Agrotechnology Transfer (DSSAT) (www.dssat.net). Increasingly, "documentation" is seen as both the description of the equations and access to the code (Badham *et al*., 2019).

Further, the software needs to be available to users for the duration in which it is used in regulation, which can be many years. During that time there will usually be developments in the science included in the model (i.e. changes to the equations implemented) and improvements in the software, be they fixing bugs or adding new features. Thus, there need to be methods and protocols for monitoring and maintaining the model (Moore *et al*., 2014; Badham *et al*., 2019). For example, the continuous development and improvement of the APSIM model is governed by formal but still relatively simple control over software versions and testing of changes or improvements against known data (Holzworth *et al*., 2011). If the use of the model goes on for long periods, there also needs to be a succession plan for scientists and software engineers behind the model to maintain knowledge of the model (equations in the model and how they were implemented) and software. Models often serve as "boundary objects", facilitating communication and increased understanding (i.e. co-learning) between the modellers and various stakeholders (Jakku and Thorburn, 2010). This learning is often the source of true value of applying models in regulation and other practical domains (e.g., decision support). The participation of people knowledgeable about the model is critical to achieving this value and an important objective of succession of personnel behind long-lasting models. Good documentation and open code help this succession. Historically, this succession planning has often been overlooked in agricultural or environmental models, with it happening by accident rather than design, if at all.

As noted above, models applied in a regulatory context will usually be implemented by a community beyond the original model developers. Additionally, the results may be closely scrutinised because of the effect they have on real-world actions. Transparency in a model's development assist the first group, the implementers, to understand the model and apply it correctly. Transparency of the science behind the model and the application process also helps those affected by the impact of model results understand that that the results are sound, and the influence on their actions in accord with the intention of the regulation.

While there is no one “test” for transparency, if many of the steps discussed above are undertaken and revealed to the implementation and impacted communities, those communities understand and have confidence in the process and results. A fit-for-purpose model structure, and quality model testing and assessment are important for building trust. Good and open documentation and code also build trust, as will a competent and ongoing implementation team. Commenting on Overseer’s transparency is outside of the scope of this peer review, so we only note that trust in models is an important criterion of their fitness-for-purpose.

4.5 CONCLUSION

We need models to underpin regulation of diffuse source pollution from agricultural systems. Such models can take many forms (empirical or mechanistic, deterministic or stochastic, dynamic or steady state). Any model must be fit-for-purpose. For even the most basic model, this means that it is based on good data and sound mathematics that appropriately represent the underlying processes. The model must also be rigorously tested and evaluated to ensure it is adequate for its intended use. We will now turn our attention to assessing how well Overseer measures up to the vision for best practice modelling we have just outlined, to determine the extent to which we can have confidence that its modelled outputs provide us with estimates of the direction and magnitude (and associated error) of changes in nutrient losses due to changes in farm management. In Chapter 5 we will discuss Overseer’s overall structure, followed by Chapters 6-8 looking at the detail of model components. Finally, we return to the overall model structure (Chapter 9) and discuss the implications of aspects of Overseer’s modelling approach for its fitness-for-purpose for its current use in decision support and regulation (Chapter 10).

Part 2: Kaupapa

5 Overview of Overseer

The purpose of this review is to assess Overseer as a decision support tool and in the context of the regulation of freshwater. We first look at the overall model structure, and what Overseer aims to do (Overseer Ltd, 2020a):

> "*OverseerFM uses science models to analyse the impact of farm management on the flow of nutrients through your farm system. It generates balanced nutrient budgets for seven key farm nutrients that estimate the amount of Nitrogen (N) leaching at the root zone and Phosphorus (P) surface run-off. It also models the amount of Methane, Nitrous Oxide and Carbon Dioxide generated on farm and the amount of carbon [sequestered] in trees*."

As with any model of a complex agricultural system, Overseer comprises a group of modules describing the individual components and how they interact. For Overseer, the main components are the descriptions of animal growth and metabolism, plant growth, and soil water and nutrient dynamics.

We agree with the PCE's assessment that it is a "largely empirical, deterministic, and steady-state model" (PCE, 2018, p. 25) as Overseer comprises both empirical and mechanistic model components. There are five basic structural characteristics to Overseer:

1. It uses a form of average climate rather than daily climate inputs, even though daily climate data are routinely available;
2. It runs on a monthly timestep, except for the hydrology model which has a daily timestep and then results are aggregated to monthly values;
3. Animal production is a defined input rather than responding to feed availability, with pasture production back calculated[11] from animal production and supplied supplementary feed;
4. Crop yield is pre-defined; and
5. It does not explicitly consider ammoniacal nor organic nitrogen dynamics and losses from farm, limiting its focus to nitrate losses.

In addition:

- When Overseer was first constructed it was based on easily available data. This led to the structural choices above.
- Overseer assumes "actual and reasonable inputs" (Watkins and Selbie, 2015, p. 29). Therefore, there is no automatic check to see if a farm system is viable; it relies on experts to do the sense-check.
- It assumes "good management practices (GMPs) are followed" (Watkins and Selbie, 2015, p. 29). We understand that regional councils who use Overseer in their plans define the relevant GMPs.
- Overseer assumes steady state conditions and that the farm system is in "quasi-equilibrium" (Watkins and Selbie, 2015, p. 29). This means it assumes inputs and site characteristics are in equilibrium with farm production. This is not always the case, for example when a farm is transitioning between land uses or there are extended periods of high or low rainfall.
- Overseer produces long-term annual averages, assuming that management, inputs, and production are constant from year to year for a given site.

When modelling agricultural systems, it is conventional to describe plant growth in response to climate for the plant and soil characteristics being considered. For pastures, animal growth and metabolism is related to intake of available pasture, along with pasture quality, and any supplied supplementary feed. These calculated values (plant and animal growth) along with other system characteristics (e.g., soil water and nutrient status) are generally referred to as emergent properties. This approach is described in Figure 5.1. As mentioned above, Overseer adopts a different approach (Figure 5.2). For pastures, animal metabolic requirements are predefined which, along with known supplementary feed supplied and defined pasture utilisation, is used to back-calculate pasture growth. For crops, crop yield is used as an input which, along with prescribed sowing date, is used to back-calculate crop growth through time. Overseer's approach is described in Figure 5.2. We shall return to this model structure in more detail in Chapter 9.

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[11] Note that one perhaps surprising consequence of the back-calculation of pasture and crop growth is that they do not respond directly to fertiliser inputs. Overseer assumes that fertiliser applications are consistent with production.

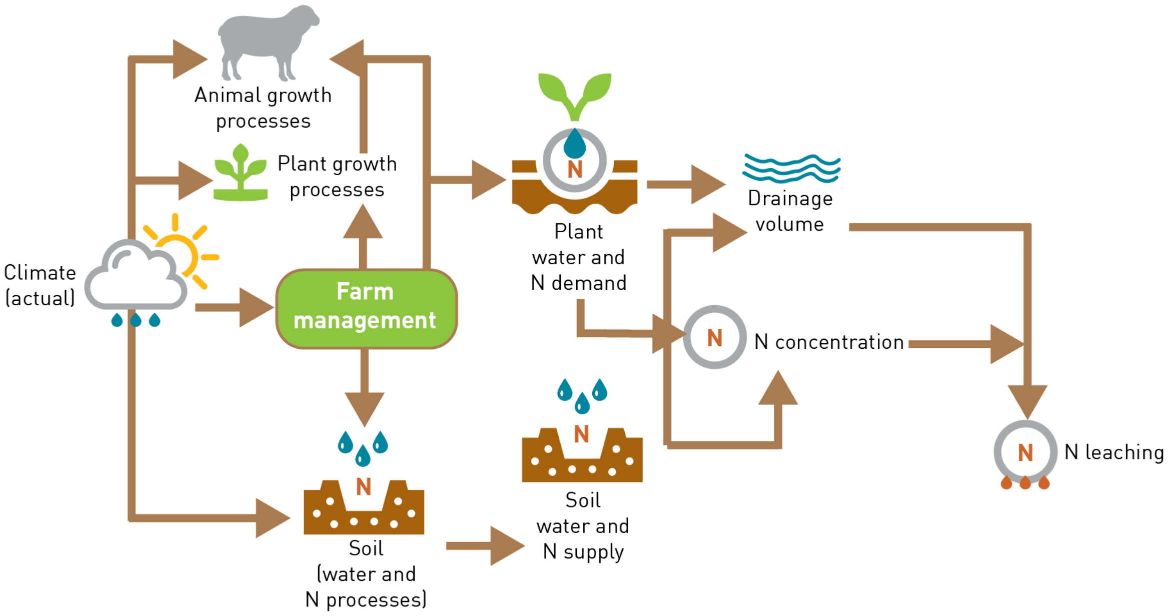

Figure 5.1 Simplified representation of a typical agro-ecosystem model, where the arrows indicate the influencing factors. Inputs are shown in bold and the emergent properties in italics. NB: The link between animals and nitrogen is omitted for simplicity.

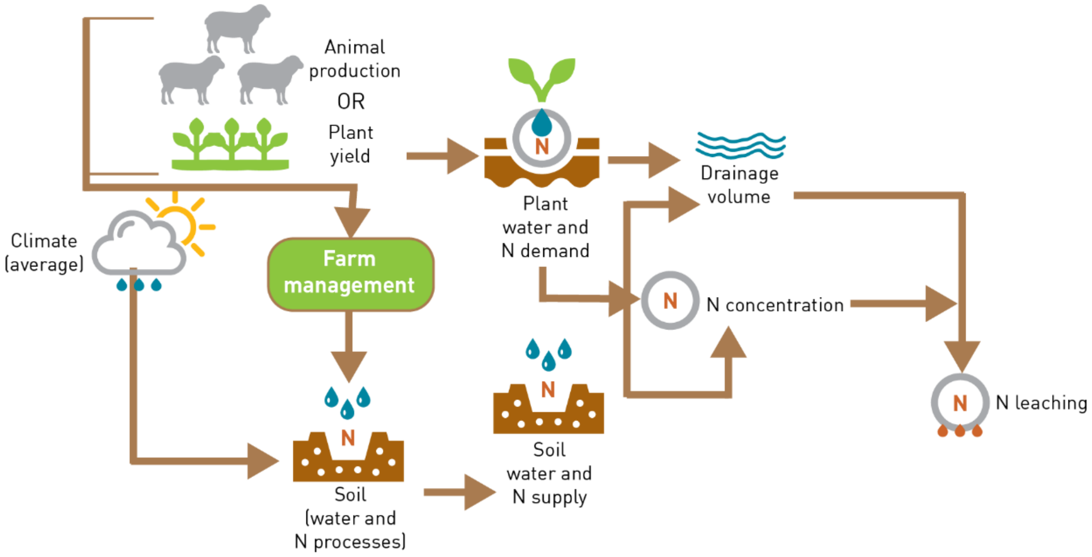

Figure 5.2 Simplified representation of Overseer, where the arrows indicate the influencing factors (as in Figure 5.1). The link between animals and soil nitrogen is again omitted for simplicity.

To run the model, it is necessary to prescribe climate inputs, define appropriate parameters (such as soil characteristics, animal type (where relevant), crop type, and so on), and then define management including fertiliser or irrigation inputs. A full list of inputs is available in Appendix One: Inputs**.** Overseer includes a comprehensive set of management options that aim to reflect the wide range of management strategies applied in Aotearoa New Zealand farming. We do not focus specifically on these options, but on the underlying scientific model structure. A detailed description of features, such as detailed farm description and inputs, can be found at https://www.overseer.org.nz/our-model.

5.1 CLIMATE

We shall now look at the way Overseer deals with climate inputs. Climate data are fundamental drivers of the core processes in any agricultural system. “*Climate data, such as temperature, rainfall, potential evapotranspiration and sunshine hours are important drivers of processes within Overseer*” (Wheeler, 2018k, p. 1). However, rather than use actual daily climate data, Overseer uses a form of climate data averaged over 30 years (1981-2010); these are monthly averages, except for rainfall which is a form of daily average distribution.

Overseer has 15 daily rainfall distributions and one of these is used depending on user inputs. These daily rainfall distributions have been constructed by NIWA based on five rainfall classifications (dry to extremely wet) and three seasonal variation classes (none to weak, low, moderate). The user defines the location and seasonal characteristics which determines which of the rainfall distributions is used. Consequently, the rainfall used is not based on real, site-specific data. It should, however, be noted that the users can enter their own average monthly rainfall values and, if they do so, the daily values in the relevant NIWA data set are adjusted so that the monthly totals calculated from the revised data are consistent with the user-defined monthly values.

The use of average climate data may have been a reasonable pragmatic decision during Overseer's initial development, but this is difficult to justify now when daily climate data are readily available from the National Institute of Water and Atmospheric Research (NIWA) (NIWA, 2020). Furthermore, is the concept of an average climate meaningful? What information is lost by not using actual climate data and analysing results for average behaviour and variation around the average? If Overseer were being developed today, we would not be asking these questions. When we look around at our everyday lives, we see detailed data and its corresponding analysis everywhere – for example, we can all get detailed weather forecasts for any city in the world almost immediately.

NIWA VCSN (NIWA, 2020)

NIWA (the National Institute of Water and Atmospheric Research) Taihoro Nukurangi has a network of virtual climate stations on a regular (approximately 5km) grid covering New Zealand.

The data are daily estimates of:

- Rainfall
- Potential evapotranspiration
- Air and vapour pressure
- Maximum and minimum air temperature
- Soil temperature
- Relative humidity
- Solar radiation
- Wind speed

These estimates are produced every day based on spatial interpolation of actual data observations from climate stations (Tait *et al*., 2006).

To consider the concept of average climate data, we have analysed one site in Canterbury (-43.725, 171.775) and have analysed pasture growth rates using these data in a pasture simulation model in use in Australia (A model with similar structure has been applied successful in both Australia and Aotearoa New Zealand, Cullen *et al.,* 2008). The analysis is in Appendix Two and is discussed in Chapter 9.[12] To set the scene, some results are presented here.

The climate data used were for the period July 1990 to July 2020. Using full years (1991-2019), the years were ranked in order of annual rainfall. Monthly rainfall for the median year (1994, 732 mm) and the two closest years 2019 (724 mm) and (2003, 745 mm) are shown in Figure 5.3. It is self-evident that the pattern of rain throughout the year is quite different for these years.

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[12] It was our intention to look at the average climate data used by Overseer alongside the actual data discussed here but, although we requested the data from Overseer Ltd, it was not provided to the panel.

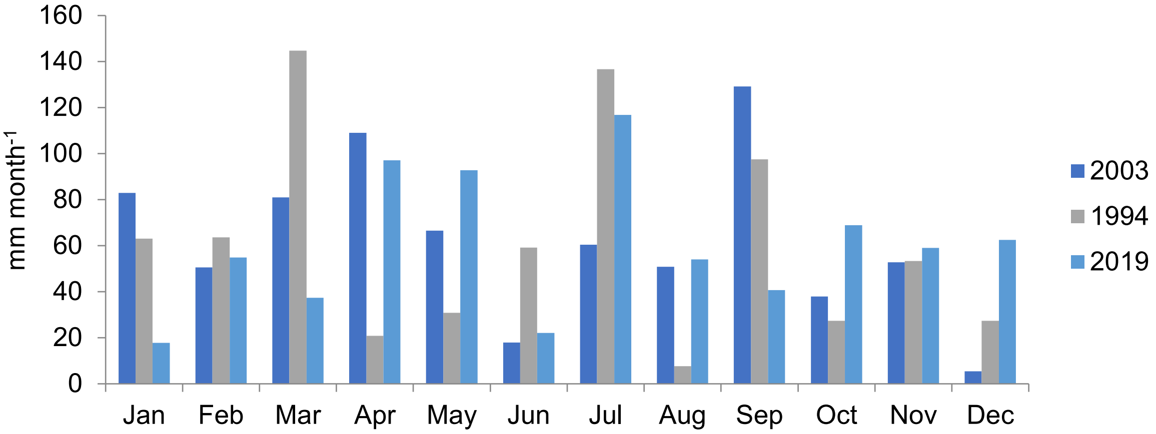

Figure 5.3 Monthly rainfall for 1994, which had the median annual rainfall, and the two years with closest values to this.

At this point, the notion of using average climate data comes seriously into question; each year is different. It appears that the use of average climate data is largely historical and relates back to times when appropriate data were not available, although this has not been the case for quite a few years.

As we have mentioned, daily climate data for a wide range of locations are now routinely available. In the past when this was not the case it was common to use 'weather generators', and these are still used for regions where such data are not available. These take known statistical properties of the climate and generate synthetic datasets with the same characteristics using mathematical techniques such as Fourier analysis and Markov chains. The advantage of this type of approach is that an unlimited set of climate files can be generated. Early important work in relation to rainfall is given by Stern and Coe (1982) and Stern, Dennett and Dale (1982a, b). Weather generators have been recommended by the Intergovernmental Panel on Climate Change (IPCC) for exploring the impact of climate variability; there are several available. The Overseer developers have chosen not to include climate variability in their analysis, and, in a sense, their constructed average climate data represent a single set of synthetic climate data based on available statistical characteristics. In a review of Overseer's climate component, Horne (2014) commented that "Obtaining a set of daily rainfall values from the mean monthly values is problematic, as there is no typical set of values…the resulting daily rainfall distributions are quite arbitrary" (Horne, 2014, p. 11).

The use of a monthly timestep, rather than daily, also appears to hark back to the situation where daily climate data were not readily available and, perhaps, when climate data were entered manually. Rather than ask the question, why use monthly rather than daily climate data, perhaps the question should be why not use daily since this is readily available. Note that using long-term actual daily climate data can still yield a long-term average estimate of nutrient losses; the averaging is simply done on model outputs rather than inputs. Importantly, this does not impose any extra complexity on the user or the regulator as these data could still be pulled in from existing databases. One might think that using daily climate data requires the user to input daily management data, and an advantage of using monthly climate data is that it is consistent with entering management data monthly. However, this is not the case; requiring that management is prescribed on a particular date does not imply that management data need to be entered daily. For example, a sheep wool enterprise may only alter stock numbers once or twice a year. There is, therefore, little to be gained and much to be lost in this approach. Climate is discussed in more detail in Appendix Two and 9.2.

As mentioned above, Overseer uses user-defined plant and animal production. For pastures the user enters animal production and supplementary feed and the model back-calculates pasture production with an assumption of a fixed pasture utilisation efficiency. For crops, the final yield is an input that determines growth from sowing. Overseer therefore does not calculate plant growth in response to climate or soil conditions. Note that this, along with the use of average climate, means system behaviour does not respond to different weather characteristics (Nonhebel, 1994).

5.2 TIMESCALES

Overseer's use of average climate data has implications for the appropriate timescale for inputs of management data. It is accepted that "Inputs must be consistent with a realistic farm system and specifically that farm management inputs reflect climate data and climate patterns" (Wheeler *et al*., 2018, p. 20). The broad options are for the user to average their management data to enter into the model, or to use their actual annual management data.

The advantage of using average management data is that management inputs are on the same timescale as the climate data. However, while climate data is averaged over 30 years of data, the timescale for averaging management data is not clear. The method for averaging management data is also unclear, particularly for activities such as stock numbers or supplementary feeding. Furthermore, there is insufficient experimental data to make a robust recommendation on the appropriate timescale and method for averaging management inputs. Therefore, Overseer developers have made a preliminary recommendation of averaging over a minimum of five years but have noted that further work is needed to define options for and implications of averaging (Wheeler *et* al., 2014; Wheeler *et al*., 2018).

Annual management inputs are typically used to collate a year's worth of data and estimate average outputs, based on aggregating annual results over several years. This is the approach used by several regional councils (see 2.2). It is important to avoid inconsistencies between annual management data and average climate data. Irrigation application rates are an example; using irrigation rates applied during unusually wet or unusually dry years in combination with average climate data can lead to over- or underestimation of model outputs (Wheeler *et al*., 2014; Wheeler *et al*., 2018). This has also been raised in Environment Court proceedings considering the use of Overseer by regional councils. A submitter was concerned that using Overseer to estimate nitrogen leaching losses with annual management inputs but with average climate data, could overestimate the leaching loss from the farm (Chrystal, 2019). Therefore, using annual management data should be done with caution. Overseer's developers currently recommend averaging model outputs over a minimum of five years to create an average output, for example using a five-year rolling mean (Wheeler *et* al., 2014; Wheeler *et al*., 2018). It appears that the choice of five years is based on opinion rather than quantitative analysis.

The use of a monthly timestep can be justified, in part, because of that simplicity of allowing users to supply management inputs on a monthly basis. Other sub-models, however, need to operate on a shorter time-step. In general, for modelling, provided the code is well-structured, then the underlying scientific model structure should be able to accommodate inputs from the user interface across multiple timeframes. As such, changing the model structure to accommodate a more frequent time-step does not necessitate changes in the complexity of the user interface, though it does open up the opportunity to add additional precision into the way in which users specify inputs.

5.3 NUTRIENT FORMS

Nutrient dynamics are discussed in detail in Chapter 8, but we briefly note here Overseer's focus in modelling nutrients.

Inorganic nitrogen in soils is primarily in the form of nitrate (NO_3^-) and ammonium (NH_4^+). Fertiliser and urine inputs are generally in the form of urea ($(NH_2)_2CO$), which quite rapidly converts to ammonium and ammonia (see Figure 5.4). Ammonium and ammonia co-exist, with the proportion of each dependent on pH, soil temperature and moisture. Ammonia may be lost to the atmosphere via volatilisation, but only if its concentration in solution exceeds its solubility threshold. The mineralisation of urea is a biologically mediated process that is also influenced by soil pH, moisture, and temperature. In addition to fertiliser and urine, ammoniacal nitrogen is released during the breakdown (mineralisation) of organic matter (which can be dung or dead plant material). In response to breakdown, mineralised nitrogen may be sequestered or released by the microbial biomass into solution. Plants can take up either ammonium or nitrate, although there is a slightly greater energy cost to take up nitrate (Johnson, 1990). Phosphorus losses can occur in both dissolved and particulate organic and inorganic forms[13,14]. These processes are well-established and understood (Walker and Syers, 1976; Moldan and Černý, 1994; Crews *et* al., 1995; Follet and Hatfield, 2001; Samarelli, 2011; Bleam, 2016).

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[13] https://link.springer.com/referenceworkentry/10.1007%2F978-3-319-39193-9_155-1#:~:text=Dissolved%20organic%20matter%20is%20a,the%20biogeochemical%20cycling%20of%20carbon

[14] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/dissolved-inorganic-phosphorus
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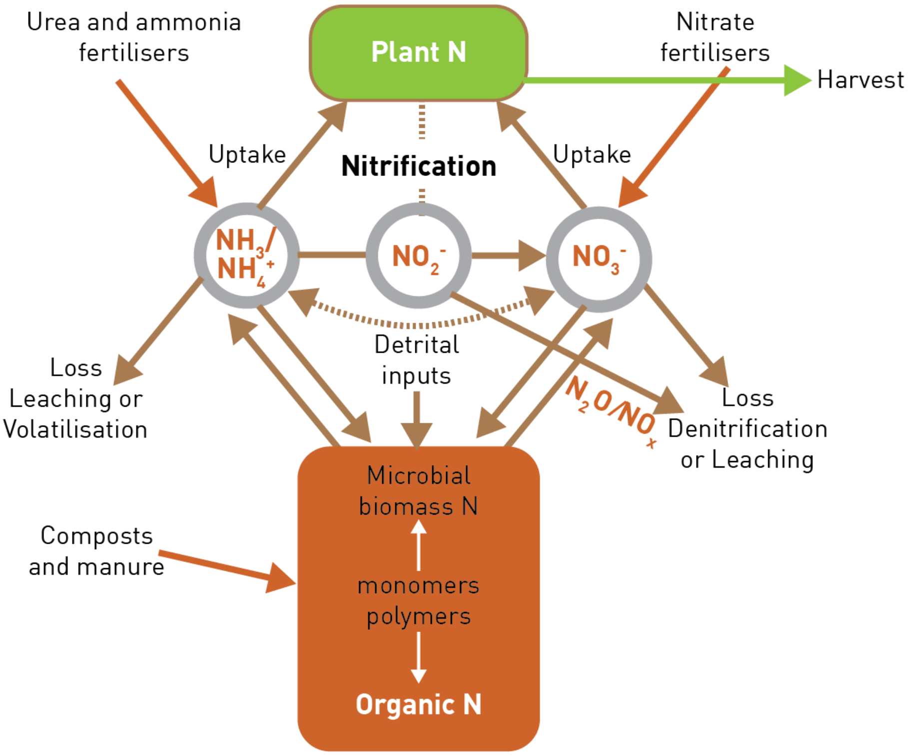

Figure 5.4 The nitrogen cycle in agricultural systems (Norton and Ouyang, 2019)

In most mineral or non-wetland soil types, the dominant form of nitrogen below the root zone is nitrate, with a potentially important contribution from small dissolved organic nitrogen forms and potentially ammonium when manure loading rates are high. Other forms of nitrogen, particulate organic nitrogen, larger dissolved organic forms, and to a lesser degree ammonium seldom percolate to these depths due to physical exclusion (filtering), electrostatic attraction, and other biogeochemical processes (Follet and Hatfield, 2001; Samarelli, 2011; Bleam, 2016). These forms of nitrogen tend to accumulate at or near the soil surface and become entrained during episodic runoff events, especially where soils are fine-textured or slowly permeable, or slope is a key factor influencing the hydrological flow path. The effect of hydrological pathways on nitrogen forms is well-established in biogeochemical literature, with episodic runoff commonly containing higher concentrations of these forms of nitrogen relative to nitrate (Moldan and Černý, 1994; Follet and Hatfield, 2001; Inamdar, 2011; Samarelli, 2011). Accordingly, soil drainage trials that utilise lysimeters and soil suction cups to collect soil drainage from below the root zone will preferentially sample nitrate over other forms of nitrogen for most mineral soils (see Shepherd *et al.*, 2011; Watkins and Shepherd, 2014; Shepherd and Selbie, 2019).

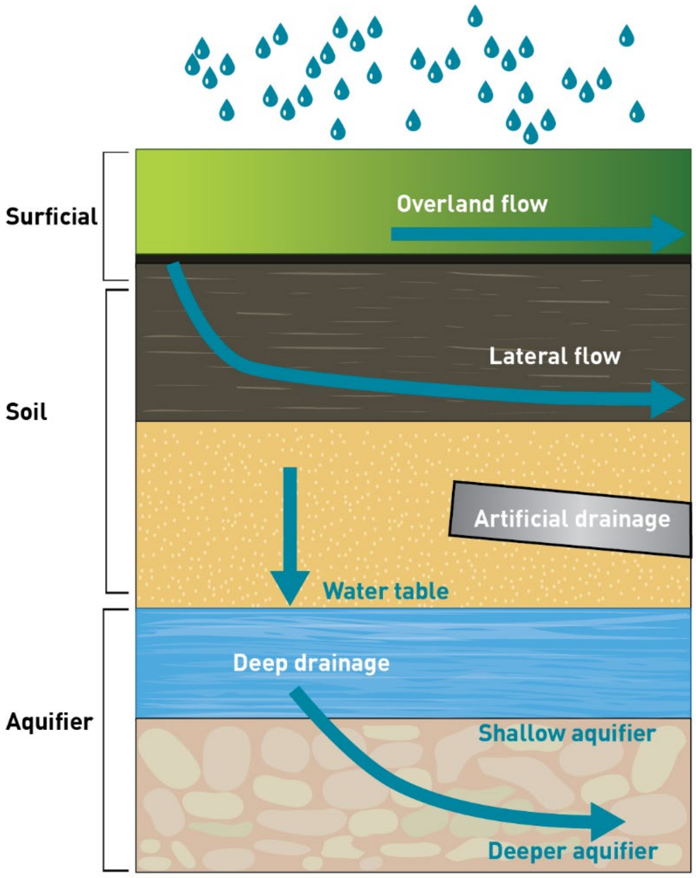

Figure 5.5 Conceptual model of hydrological pathways relevant to nutrient export from farm. Literature review shows that Overseer farmlet calibration studies are primarily based on losses from below the root zone.

For artificially drained soils (mole-pipe drainage type), the potential range of nitrogen forms entrained during deep drainage beyond the root zone will vary according to the soil's carbon content and soil water residence time, which is related to the effectiveness of the drainage system[12]. Table 5.1 provides a summary of the different forms of nitrogen collected from 26 different tile drain outfalls across Southland (Environment Southland data for the period 2011-2017; Table 5.1).

Table 5.1 Nitrogen forms for 26 artificially drained (mole-pipe type drainage) soil waters collected during the winter months across Southland (Environment Southland data). Median values, parts per million (ppm), are used to calculate %nitrate-nitrite nitrogen.

	Total nitrogen	Total Kjeldahl nitrogen	Total ammoniacal nitrogen	Nitrite nitrogen	Nitrate nitrogen	Nitrate-nitrite nitrogen	% nitrate-nitrite nitrogen
Valid cases	20	21	22	18	20	26	20.0
Mean	2.5	2.1	0.03	0.03	2.0	1.6	24.1
Median	1.6	1.0	0.02	0.01	0.4	0.2	1.6
Standard deviation	2.8	3.1	0.03	0.09	3.3	3.0	34.3
Standard error	0.6	0.7	0.01	0.02	0.7	0.6	7.7
Coefficient of variation	1.1	1.5	1.03	2.80	1.6	1.9	1.4
Minimum	0.6	0.4	0.01	0.00	0.0	0.0	0.2
Maximum	13.3	13.2	0.14	0.40	13.1	13.1	88.2

% nitrate-nitrite nitrogen values are calculated from median values. % nitrate-nitrite nitrogen is the percentage of nitrate nitrite nitrogen relative to total nitrogen. These samples were collected across the Southland region, mainly as one-off grab samples, although some sites had as many as four repeat measurements (treated as a median score). Please note this table is not designed to be read from left to right.

Although the dataset is small, does not address temporal variability, and is biased towards imperfectly to poorly drained soils, it suggests that nitrate-nitrite nitrogen (NNN) may constitute a relatively minor fraction of the total nitrogen exported from farm to river networks by mole-pipe drainage. Specifically, median %NNN (percentage of NNN relative to total nitrogen) is 1.6% with a maximum of 88.2% and a minimum of 0.2% (Table 5.1). Using S-map and the Fundamental Soils Layer (FSL) for the areas where S-map is not available, the extent of imperfectly to poorly drained soils is calculated at 9,687,772 hectares or approximately 56% of the productive land area of Aotearoa New Zealand (Table 5.2). The export of nitrogen in forms other that nitrate can be considerable. A large number of research articles document the importance of these forms of nitrogen in terms of internal nutrient cycling and the attendant ecosystem health of riverine, lake and estuarine ecosystems (Seitzinger and Sanders, 1997; Moldan and Černý, 1994; Follet and Hatfield, 2001; Capone *et al*., 2008; Samarelli, 2011; Eom *et al*., 2017; Xie *et al*., 2019).

Table 5.2 Soil Drainage Class for Aotearoa New Zealand's productive land (S-map and FSL)

	Area (ha)	Class percentage (%)
5. Well-drained	7,619,222	43.8
4. Moderately well-drained	3,500,282	20.1
3. Imperfectly drained	4,525,109	26.0
2. Poorly drained	1,428,659	8.2
1. Very poorly drained	233,722	1.3

The potential for significant variation in the forms of nitrogen exported from farm to waterways is supported by an evaluation of the %NNN relative to total nitrogen in Aotearoa New Zealand's rivers using the Land, Air, Water Aotearoa (LAWA) database[15] (Figure 5.6; Table 5.3). The dataset reflects a five-year median for 2015-2019 and 795 surface water monitoring sites nationally. Monitoring sites down gradient of point source discharges and those dominated by urban areas have been excluded.

FSL (Manaaki Whenua, 2021)

The FSL contains information for 16 key soil attributes:

- Slope
- Potential rooting depth
- Topsoil gravel content
- Proportion of rock outcrop
- pH
- Salinity
- Cation exchange capacity
- Total carbon
- Phosphorus retention
- Flood interval
- Soil temperature
- Total profile available water
- Profile readily available water
- Drainage
- Macropores (shallow and deep)

It covers the whole of mainland Aotearoa New Zealand. The FSL can be accessed from https://lris.scinfo.org.nz/.

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[15] LAWA is a partnership between regional councils, government, universities and research organisations. It aims to help local communities balance using natural resources and maintaining the quality and availability of resources by sharing environmental data and information.

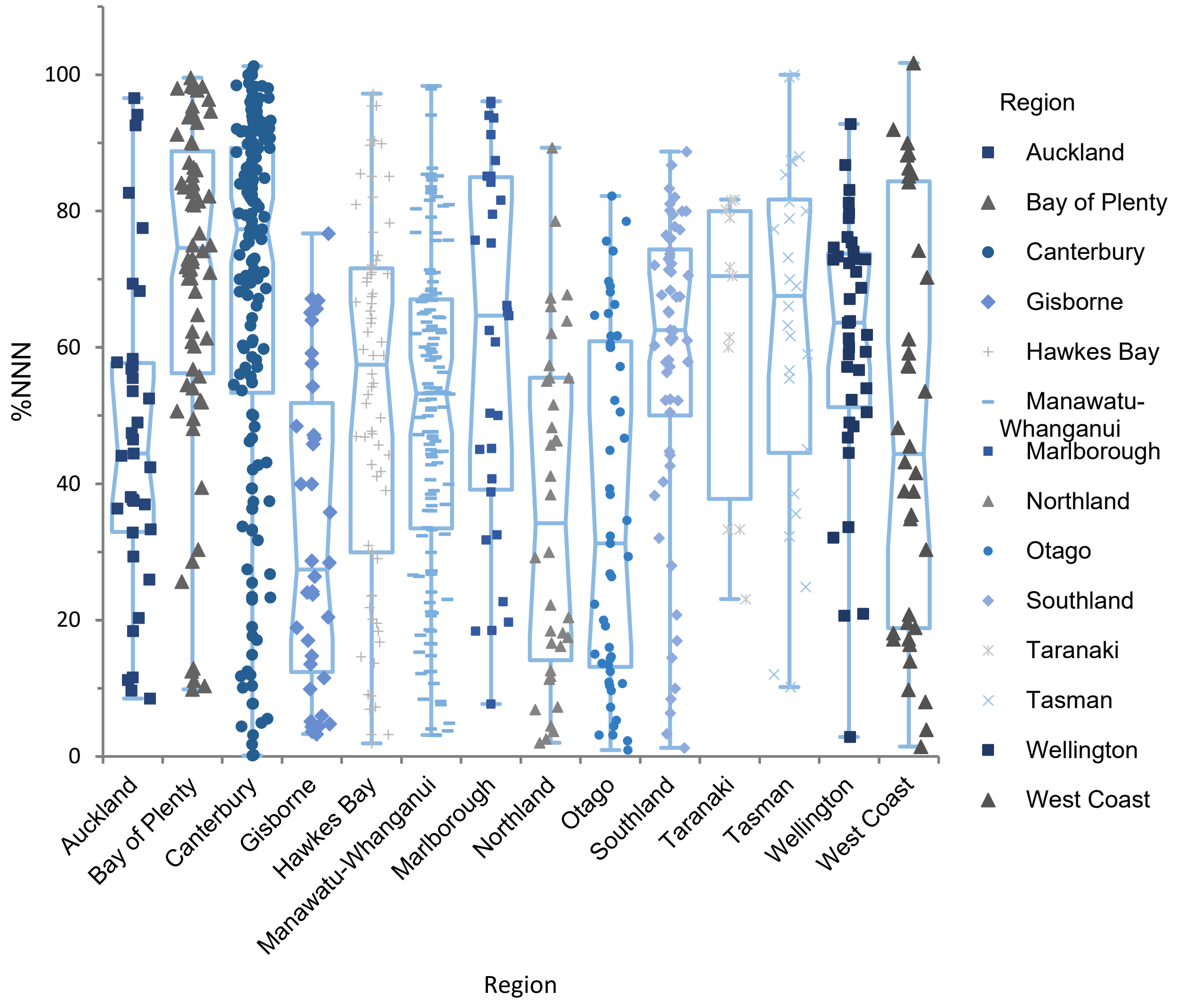

Figure 5.6 Box-and-whiskers plots (95% confidence interval) of the %NNN as a fraction of total nitrogen by region (median values LAWA dataset 2015-2019).

Figure 5.6 and Table 5.3 show a large degree of variation in the %NNN within each region. In addition to land use and variable instream processing, this variation is probably due to the role of spatial variation in landscape factors, such as topography, soil type, and geology over the generation, storage, transport, and transformation of nitrogen. Variation in nitrogen forms may occur at catchment, sub-catchment and even stream reach scales in response to variation in landscape properties such as topography, soil, and geology (James and Roulet, 2006; Rissmann *et al*., 2018; Wu and Lu, 2019). Irrespective of the various processes driving variation, the main point of this high-level assessment is to demonstrate that significant variation in the forms of nitrogen occurs across Aotearoa New Zealand's river networks. Further, the concept that nitrate is the only nitrogen form of importance in biogeochemical cycling and ensuing eutrophication of waterways is out of step with international peer-reviewed literature (e.g., Seitzinger and Saunders, 1997; Moldan and Černý, 1994; Follet and Hatfield, 2001; Capone *et al*., 2008; Lewis *et al*., 2011; Samarelli, 2011; Eom *et al*., 2017; Xie *et al*., 2019). There is a large body of educational and academic literature outlining the important role of internal cycling of particulate and dissolved forms of nitrogen and phosphorus over the eutrophication of rivers, lakes, and estuarine and marine environments for those interested in the phenomenon[13,14,16].

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[16] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/particulate-organic-nitrogen

Table 5.3 Tabular summary of %NNN in surface water as a fraction of total nitrogen by region (median values, LAWA dataset 2015-2019).

%NNN of total nitrogen by region	Minimum	First quartile	Median	95% confidence interval		Third quartile	Maximum
Gisborne	4.3	14.6	29.4	20.3	55.9	61.1	79.3
Otago	1.1	13.4	33.3	16.8	51.7	65.8	88.2
Auckland	4.6	17.4	33.7	18.0	44.4	45.2	93.0
Northland	4.2	17.8	40.0	20.5	62.2	63.6	95.3
West Coast	1.6	20.6	49.5	31.7	65.8	87.3	101.2
Manawatū-Whanganui	9.0	39.8	59.3	49.3	68.6	73.8	91.3
Hawkes Bay	2.4	35.9	63.6	53.1	71.0	78.0	98.6
Wellington	3.4	53.8	67.0	55.8	75.9	77.7	96.5
Tasman	10.5	42.6	67.8	46.3	81.5	81.6	100.0
Marlborough	9.0	46.2	68.5	48.3	86.8	87.6	97.0
Southland	1.9	53.7	71.8	62.0	76.8	79.6	93.5
Waikato	2.0	57.8	71.9	65.7	75.4	81.5	94.8
Taranaki	24.2	40.1	75.0	34.0	87.4	85.1	88.5
Bay of Plenty	13.1	57.7	76.9	66.2	82.2	85.2	98.3
Canterbury	1.0	52.3	80.1	71.0	86.1	92.1	102.2
Nelson	-	-	-	-	-	-	-

Bearing in mind the generalisations associated with lumping regional data, it is notable that Canterbury, Bay of Plenty, Taranaki (small sample size), Waikato, and Southland have median %NNN values between 70 and 80% (Table 5.3). In contrast, Gisborne, Otago, Auckland, Northland, and the West Cost have median %NNN between 29 and 50% (Table 5.3). In these regions, therefore, at least half of the nitrogen measured occurs as organic and/or ammoniacal forms. The remaining regions fall between these two endmembers, and all exhibit a significant organic and/or ammoniacal nitrogen fraction relative to total nitrogen. Overall, only 182 sites or 23% of the sites in the dataset have %NNN greater than or equal to 80%, with the remainder having a significant component of non-NNN nitrogen. Key here is that all regions exhibit significant variation in nitrogen forms.

Current data notwithstanding, the relative contribution of the different nitrogen and phosphorus forms to waterways is still poorly constrained. This appears to reflect a deficit in the sampling of runoff from farms and event-driven sampling across Aotearoa New Zealand’s surface water monitoring network. A lack of sampling of surface runoff and event sampling underpins much of the uncertainty surrounding the relative contribution of particulate, ammoniacal and dissolved organic forms. Event sampling is important as particulate, ammoniacal, and dissolved organic forms of nitrogen are predominantly mobilised in response to episodic runoff. Issues of data paucity relevant to critical water quality controls have recently been identified as a key limitation over the understanding of water quality controls nationally, with the Parliamentary Commissioner for the Environment identifying “huge data gaps” in the content and quality of national datasets relevant to effective decision making (PCE, 2019)[17].

Given the above context, it is important to evaluate what forms of nitrogen loss Overseer is actually estimating. Overseer reputedly estimates total nitrogen (i.e., all nitrogen forms exported from farm). However, it has been difficult to find any specific reference to totals, with most of the literature reporting on root zone losses of nitrate (see Shepherd *et al.*, 2011; Watkins and Shepherd, 2014). Further, the terms nitrate and nitrogen and N appear to be used interchangeably in much of the documentation, making it difficult to decipher what Overseer is estimating.

Some clarity over what Overseer is estimating may be gleaned from Watkins and Shepherd (2014) who published a “compendium of New Zealand farmlet experiments measuring nitrogen leaching”. These authors state that “The aim of this paper is to identify and catalogue pasture farmlet experiments that have focussed on measuring N leaching losses as well as including measurements of productivity. These experiments serve as a critical resource for (a) testing the principles behind farm system models such as *Overseer* and (b) calibrating or validating such models” (Watkins and Shepherd, 2014, p. 1). Within this experiment, it is apparent that:

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[17] Focusing Aotearoa New Zealand’s environmental reporting system November 2019. Parliamentary Commissioner for the Environment Te Kaitiaki Taiao a Te Whare Pāremata PO Box 10-241, Wellington 6143 Aotearoa New Zealand.

- the majority of farmlet trials suitable for Overseer calibration have focussed on nitrate leaching below the root zone (approximately 0.4-0.6m), utilising lysimeter and soil suction cups as the main measurement tools; and
- most soils reported in this compendium appear to be well-drained mineral soils.

The challenge with the empirical context provided by the farmlet studies reported in Watkins and Shepherd (2014) is that they seem to be inherently biased towards well-drained mineral soils and lysimeter and suction cup measurements that naturally favour nitrate leaching via vertical percolation (deep drainage) through the soil matrix (Figure 5.5). No mention is made of the measurement of nitrogen loss from surficial flow paths. Furthermore, Watkins and Shepherd (2014) conclude their review of farmlet studies by noting that “The N leaching measurement method must also be suitable and it is important that measurements are taken at an appropriate depth (generally >500 mm) because, otherwise, this could overestimate N leaching if ‘leached’ N is subsequently recovered by deeper roots”. While we understand this recommendation was to ensure that nitrogen leaching losses were not overestimated, this advice unintentionally recommends a measurement technique that is more likely to result in nitrate being sampled and other forms of nitrogen being excluded. [18]

Accordingly, surface runoff events that transport particulate organic nitrogen, macromolecular forms of dissolved organic nitrogen, and ammonium to waterways do not appear to have been evaluated, nor used for the calibration of Overseer. The same issues apply to more recent validation of Overseer’s nitrogen leaching sub-model (Shepherd and Selbie, 2019). The vast majority of validation datasets reported are associated with well-drained soils, most use lysimeters and a few use ceramic cups, the majority collect drainage at 0.6-0.7m depth, and all the data come from Waikato or Canterbury. The absence of trials assessing surface nitrogen losses and the small range of soil and landscape settings across which Overseer has been trialled raises questions about the meaningfulness of its nitrogen loss estimates in terms of the total amount of nitrogen exported from farm. This is particularly important for the large area of New Zealand for which surface runoff constitutes an important hydrological pathway of contaminant loss. The limitations of extrapolating Overseer beyond the narrow range of calibration sites have long been raised by scientists involved in Overseer’s development (Watkins and Shepherd, 2014; Shepherd and Selbie, 2019).

In summary, although Overseer reputedly estimates total nitrogen exported from farm, a bias towards i. well-drained mineral soils; ii. calibration trials that appear to have only considered vertical percolation (deep drainage) of soil water below the root zone as the main pathway of nitrogen loss; and iii. measurement techniques that favour the sampling of nitrate raise the possibility that a significant fraction of the nitrogen loss associated with episodic and surface runoff is not accounted for by the model. Episodic runoff events occurring in response to saturation and infiltration excess overland flow are a common occurrence and play an important role in the delivery of contaminant loads to Aotearoa New Zealand’s freshwater ecosystems.

5.4 CONCLUSION

Overseer is a deterministic, steady state model that does not capture responses to actual climate data and the associated management variation. It has many empirical components and some mechanistic components. An unusual feature of its structure is the back-calculation of pasture or crop growth from user-defined production data. This, in combination with the use of average climate data, means that it does not model how systems respond to climate variability. The use of average climate data also has implications for the types of management data that should be included.

Critically, the data used in Overseer’s development were biased towards deep drainage (vertical percolation of water below the root zone) and did not appear to account for episodic losses of other

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[18] Of the studies assessing nitrogen losses from imperfectly drained soils, the long-term Tussock Creek study in Southland is associated with the poorly drained Pukemutu soil series (TopoClimate South, 2002). Pukemutu soils are formed in loess (silt) derived from tuffaceous greywacke and are categorised as Pallic soils according to the New Zealand Soil Classification (Hewitt, 1993). These fine-textured soils are characterised by a moderately deep potential rooting depth that is severely restricted by a fragipan at 0.6-0.9m depth. The depth of the fragipan means that water perches within the subsoil and greatly reduces aeration status. Artificial drainage of these soils is necessary for productive purposes, with mole-pipe drainage resulting in enhanced soil aeration and accelerated drainage rates (TopoClimate South, 2002). At Tussock Creek, tiles occur at 0.95m depth and moles from 0.4-0.45m depth. Mole-pipe drainage is used to isolate blocks hydrologically with drainage via the tile outfall recorded and samples taken for analysis. Accordingly, drainage water percolates through a minimum of 0.4m to mole lines before draining to the main tile line. Due to this soil's fine texture, drainage that reaches the tile line is likely to be dominated by nitrate (Samarelli, 2011). Other nitrogen forms are excluded by physical filtering, electrostatic attraction, and other biogeochemical processes. Accordingly, it is unsurprising that nitrate dominates drainage at the tile outflow at greater than 0.95m depth.

nitrogen forms via surficial pathways. This implies that Overseer’s estimates of total nitrogen may only be appropriate for areas for which deep percolation below the root zone is the dominant pathway of nitrogen loss, or approximately 20% of Aotearoa New Zealand’s productive land (see 8.1.2) – notwithstanding other limitations in the overall model structure.

6 Animal production and metabolism

Inclusion of animal production assessments within farming systems models designed for decision support and regulatory development and enforcement is crucial, particularly in Aotearoa New Zealand due to the prevalence of livestock operations. Nutrient emissions from livestock operations occur primarily from manure excretion (faecal and urine) of organic matter, nitrogen, and phosphorus. Bacterial contaminants and other pathogens associated with manure are also important.

In Aotearoa New Zealand, management of ruminants on pasture also presents the challenge of year-round nitrogen losses in urine patches that have high and variable nitrogen concentration; hoof action that disturbs soils and contributes to soil losses; and the additions of fertiliser and supplementary feed designed to enhance output from production systems. Nutrients leaving livestock farming systems, namely as manure, can be lost to volatilisation (ammonia NH_3), denitrification (N_2 and N_2O), leaching (predominantly nitrate NO_3^-, but also ammonium NH_4 and phosphorus in free draining soils) and runoff. Organic matter, nitrogen, and phosphorus consumed that are not utilised for maintenance or productive processes are lost. In other words, biological systems conserve mass. In dairy cows, for example, on average 72% of consumed nitrogen is excreted in faeces and urine (Castillo *et al.*, 2000) although any increase in the capture of nitrogen for productive processes, such as milk production, reduces this loss, as can careful management of dietary composition to match requirements.

Estimates vary considerably depending on the tool used for estimation, but one set of estimates show total nitrogen loading from dairy and other pastoral agricultural systems of 36.7 and 33.3%, respectively, of total nitrogen losses from agricultural systems (Howard-Williams *et al.*, 2010). One of the major challenges associated with modelling livestock systems in Aotearoa New Zealand is that operations are primarily pastoral. The majority of intensive animal nutrition research requires precise measurement of feed nutrient inputs and waste nutrient export. These precise measurements are often incompatible with the grazing environment. Alternative marker-based approaches and measurement proxies are therefore often used to try and understand the flow of material through pastoral systems. As discussed in Chapter 4, this challenge extends to regulation because measuring emissions from pastures is impractical. Diffuse pollutants such as nitrogen and phosphorus excretion in manure cannot be efficiently measured directly due to the large physical area that would need to be monitored and the expense of individual measurements. There is a history of using insights from intensive animal nutrition studies in mathematical representations of the wider ecosystem to simulate movement of non-point-source pollutants through a field, farm, or watershed.

Due to the challenges associated with measurement, modelling these complex livestock-environment interactions enables us to summarise existing knowledge, to identify gaps in our existing knowledge, to corroborate model output with experimental results or expert expectations, and to develop a better understanding of system dynamics. Modelling these complex livestock/environment interactions is, therefore, beneficial but there are several aspects of data and model structure that should be continually assessed to ensure the model is fit for use. As noted in Chapter 4.2, in general we can ask four primary questions:

1. Is the model structurally appropriate?
2. Were the data used to derive relationships representative of the systems simulated?
3. Do we expect the model to perform adequately for prediction?
4. What are the broader implications of model sensitivity and/or prediction errors?

This chapter reviews the animal metabolism component of Overseer, one such structural representation of the livestock/environment interface, in terms of its fitness for use as a regulatory tool and as a decision support tool. In considering each use, we use these four questions to investigate strengths and weaknesses. Importantly, as discussed in Chapter 4, we attempt to take a holistic approach to model evaluation.

6.1 MODEL STRUCTURE

Most farm systems models are mechanistic and dynamic, meaning that they simulate the fluxes of mass through physical systems as a function of time in a manner representing true biological and physical drivers. Overseer takes a different approach, particularly when representing livestock metabolism. Many models aim to predict animal production responses to feed intake, but Overseer uses on-farm production as an input and back-calculates intake. The general flow of this calculation is as follows:

1. Calculate metabolisable energy (ME) requirements associated with user-defined production (meat/milk/wool) data (Wheeler, 2018b).
2. Estimate ME requirements associated with maintenance based on user-defined animal body weights (Wheeler, 2018b).
3. Total ME requirements is the sum of that required for production and for maintenance (Wheeler, 2018b).
4. Estimate ME requirements remaining after supplemental feed (Wheeler, 2018a). Supplements can be homegrown crops, homegrown hay or silage, and purchased feeds and require the user to input the amount of supplement grown or brought onto the farm. Overseer has default values for the nutrient content of all supplements (Wheeler and Watkins, 2018b, p. 16).
5. Under the assumption that there will be enough pasture to meet remaining ME requirements, estimate grazed pasture intake as residual ME divided by pasture energy content (Wheeler, 2018a).

Once the intake of supplement and pasture is calculated, the excretion of nutrients is then predicted based on the difference between nutrient intake and nutrient requirements (Wheeler, 2018a). For example, protein requirements for production and maintenance are estimated following the same approach as energy requirements. Protein intake is then calculated based on the pasture and supplement intake and protein contents. Protein is converted to nitrogen based on the average total nitrogen contents of proteins. Total nitrogen excretion is estimated as the difference between intake and requirement (Wheeler, 2018a). Portions of this calculation scheme (e.g., estimation of animal ME requirements) have previously been independently reviewed (Pacheco, 2016).

The inputs for predicting total nitrogen excretion include feed types, feed composition, animal body weight, and animal production level. The outputs predicted are dry matter intake of pasture and nutrient excretion (Wheeler, 2018a). If we evaluate the sensitivity of nitrogen excretion to the various inputs:

- a 1% change in body weight yields a 0.41% change in total nitrogen excretion;
- a 1% change in feed nitrogen content yields a 0.21% change in total nitrogen excretion;
- a 1% change in body weight change yields a 0.56% change in total nitrogen excretion;
- and a 1% change in milk production yields a 0.50% change in total nitrogen excretion.

This suggests that the model is more sensitive to animal parameters (production, body weight, body weight change) than to feed parameters (total nitrogen content). These values were obtained using the Overseer model equations (Wheeler 2018a-c), basal input values representative of an average Aotearoa New Zealand dairy production system, varying each specified input by 10% above and below its basal value, and fitting a linear slope to the resulting total nitrogen excretion estimates.

Overseer's structural approach of back-calculating feed intake has the advantage, when conducting retrospective analyses, of using animal performance data. This use of previously measured farm productivity liberates the system from the burden of having to predict something that many farmers already know (production outputs). However, an important caveat of this model structure is that the relationship between inputs and diet composition must be known. Because the model does not follow a process-based structure, it cannot account for expected changes in production associated with dietary intervention unless the dietary intervention has been implemented already and production responses have been measured. As such, the model is more appropriate for retrospective comparison of management decisions rather than for "what-if" simulations associated with changing inputs to the livestock operations. This is concerning from a mātauranga Māori perspective, as key to supporting the taha wairua of Papatūānuku is being able to look to the future based on knowledge of the past; *kia whakatōmuri te haera whakamua*[19] (see 4.3).

6.2 DATA USED TO DERIVE ORIGINAL RELATIONSHIPS

Data were used to derive equations used to predict ME and protein requirements. Overseer's maintenance energy requirement equation (Wheeler, 2018b) is based on that derived by Corbett *et al.* (1987), which largely used equations from the Agricultural Research Council based on calorimetric measurements. Calorimetric studies require animals to be entirely or partially housed in enclosed chambers to measure gas exchange across the chamber (or head box). This presents obvious challenges for evaluating grazing systems because it requires cut-and-carry feeding approaches that may not mimic animal grazing behaviours. Although there are a few studies estimating carbon dioxide

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[19] I walk backwards into the future with my eyes fixed on my past.

expenditure from grazing animals that were leveraged as a part of developing these requirement schemes, the breadth of this dataset is very limited.

Estimation of energy requirements for milk production is more straightforward and is based on measurement of the energy captured in milk or in growth tissues. Milk energy is based on the heats of combustion of milk protein, fat, and lactose (Wheeler, 2018g). There are few likely data challenges associated with the similarities between milk solids used for deriving these heats of combustion and milk solids today. The estimation of milk net energy requirement is likely to be fairly precise because milk solids contents are known and provided as a user input within the model. However, the energy required for milk production is only part of the energy required by the animal – the animal also needs energy for growth and maintenance (e.g., Johnson *et al*., 2016). In addition, energy may be released as animals lose weight, particularly through fat catabolism. Thus, total energy requirements could vary based on diet, production level, physiological stage, or other factors and may be a data limitation within the model.

The estimation of growth requirements uses a similar approach to estimation requirements for lactation, in that the heats of combustion of muscle and fat tissues are used to generate a net energy requirement for growth. This calculation requires knowing the composition of muscle and fat gain in a carcass, which is expected to vary with age and diet. Modifications to the predicted composition of gain have been developed to reflect age-related variation (Wheeler, 2018b). However, calibration to forage-based diets that are expected to support lean tissue gain may be needed. Much like milk requirements, net energy requirements for growth are converted to ME requirements based on an efficiency of use. The present conversion efficiency is constant but true conversion efficiencies likely depend on diet, production level, physiological stage, and other factors.

Finally, energy obtained from or stored as body reserves are estimated in a similar way to growth energy dynamics. Body composition (muscle versus fat) is estimated based on body condition score (Wheeler, 2018b). The data used to describe body composition at different body condition scores is limited and largely obtained from non-lactating, non-pregnant cattle (Wright and Russel, 1984). True energy obtained from or stored as body reserves may differ based on diet, physiological stage, production level, and other factors.

The breadth of data available for estimating maintenance energy requirements of pastures ruminants is also limited. For example, energy requirements can vary depending on travelling time to and from sheds or for stock on hilly country. Although relationships exist within energy requirements models to account for these factors, they are based on extremely limited datasets that may not be a good representation of Aotearoa New Zealand production contexts.

The data limitations discussed here are likely to affect the usability of the Overseer model and may contribute to poorly specified relationships within the model. However, it is important to note that these limitations exist for almost any model using energy requirement estimations. Conducting sufficient additional experimentation to recalibrate existing energy requirement equations would be a tremendous undertaking both in terms of monetary and time resources. Indeed, recognising that all models reliant on energy requirement estimations suffer from these same limitations, we cannot say that Overseer differs from state-of-the-art in this context. That said, Pacheco (2016) provided numerous recommendations for areas of the ME calculation scheme that could be updated to maintain consistency with recently published scientific literature. This included pointing out several documentation inconsistencies which impeded evaluation of the model structure.

6.3 MODEL PERFORMANCE FOR PREDICTION

When looking at model performance for prediction, it must be remembered that this is not prediction of animal growth and metabolism, since this is a user input. Rather, it is a prediction of the intake required to satisfy these processes, and the subsequent excretion of dung and urine. Evaluating model performance when predicting data outside the calibration range is one strategy to evaluate model fitness. It is often of primary interest when evaluating models because numerical estimates of “error” can be determined. There are few, if any, peer-reviewed, published evaluations of the statistical goodness-of-fit of the Overseer animal model predictions in comparison with measured data. Although there is a publication discussing the accuracy, precision, and uncertainty of this model, it provides no quantitative values (Shepherd *et al*., 2013). Often, literature cites insufficient data or the non-point-source nature of emissions as justification for this lack of comparison. However, there are several animal performance studies from Aotearoa New Zealand that could be used to evaluate various calculation steps in the model. When considering how Overseer is used in practice, the setup of the model to simulate these literature studies for comparison of measured and modelled values may, in itself, present a major challenge because the model would need to be set up to match the production conditions occurring in the experiment. This means, for example, that actual and not average climate conditions would need to be used. Until more flexibility can be achieved in set up (i.e., until actual climate conditions can be used) this quantitative evaluation exercise is likely futile.

Another strategy for quantitative model evaluation is comparison with other models. The Overseer nitrogen excretion predictions were of similar order of magnitude to APSIM predictions, though significantly less sensitive to important biological and physical stimuli (Vibart *et al*., 2015). The Overseer model predictions also followed similar behaviours as the LEACHN model (Mahmood, 2017). The consistency between magnitude of predictions with those of more traditional process-based models provides some confidence in Overseer.

6.4 BROADER IMPACTS OF MODEL PREDICTIONS

There are three error scenarios to consider when contemplating the broader impacts of model errors:

1. Errors that are consistent across the possible range of the dataset;
2. Errors that are scalable with the predicted value or with important input parameters; and
3. Errors that increase or decrease in magnitude with higher predictions. In each case, the impacts of the error should be considered for policy applications and for decision support system applications.

For either application, consistent or scalable errors across the possible range of the dataset is the least concerning. If the model consistently under-predicts nitrogen excretion by 5%, it can still accurately detect directional changes and the relative magnitude of those changes. In that case, the cost of this error in the context of decision support or regulation is only notable if the model needs to predict the correct value exactly, which current guidance on the use of Overseer in regulation advises against (see Chapter 2.2). If Overseer is not required to predict the exact nitrogen excretion value in either context, its fitness for use would not be affected by this type of error. However, if exact predictions are essential, this type of error is serious.

Irrespective of whether exact predictions are needed, errors that scale with predicted value or with input parameters present a greater challenge and call into question the validity of use of the model to compare nutrient leaching scenarios, as recommended by current guidance (see Chapter 2.2). Consider the example of the model having greater prediction error for animals losing body condition, recognising that this is not something that Overseer attempts to predict. The higher the loss in body condition, the less accurate the model. Therefore, if we are evaluating one scenario where we are using supplemental feed to prevent body condition loss and a separate scenario where we are allowing body condition loss, we cannot directly compare the two scenarios to generate an expected magnitude of change. Numerically, the first scenario might predict 10 +/- 2 while the second might predict 15 +/- 5. In this example, because of the differences in precision of the two estimates we cannot even be confident in whether there was a directional change. These types of inaccuracies must be quantified to allow for more informed use of the model for either decision support or for regulation.

Finally, heteroscedasticity in errors is very common in biological models. That is, the higher the predicted value, the greater the magnitude of the inaccuracy in prediction. Much like the above scenario, this type of error could present a major challenge for either use of the model.

In order to evaluate the presence and relative importance of these types of errors, quantitative comparison of sequential model prediction steps to equivalent measured data from experiments or production settings is needed. As mentioned previously, whether Overseer can be set up for this type of quantitative comparison is also a question.

6.5 CONCLUSION

We can have confidence in the modelled outputs from the livestock metabolism components if the user is not simulating changes to livestock operating processes, or if the user is simulating a change in the number of animals grazed on a property, as long as no dietary, genetic, or other management changes are implemented. If modelled simulations require shifts in predicted animal performance, the model results may differ in reliability among scenarios. We cannot have confidence in the model's outputs when simulating changes to livestock management (i.e. dietary changes) without more comprehensive sensitivity analyses, comparison with measured data, and behavioural confirmation by community members, experts, and stakeholders. Overseer should not be used to simulate what nitrogen excretion might look like under variations in management.

7 Pastures, crops, and horticulture

7.1 OVERVIEW

Overseer models the growth of pasture, arable crops, and horticultural crops. There are some differences in the way pasture growth is represented compared with crops. However, all plant growth is based on a common philosophy – that the growth is derived either directly (crop yield) or indirectly (pastures) from productivity information entered by the user. For pastures, production from animals (i.e. meat, wool, milk) is used to specify the metabolisable energy (ME) required to achieve this production, and this requirement is met by supplements (specified by the users) and pasture growth (Figure 7.1). In the case of crops, the user specifies the yield of the crop (or each crop in a rotation), from which monthly growth is derived to allow calculation of water and nitrogen uptake on a monthly basis.

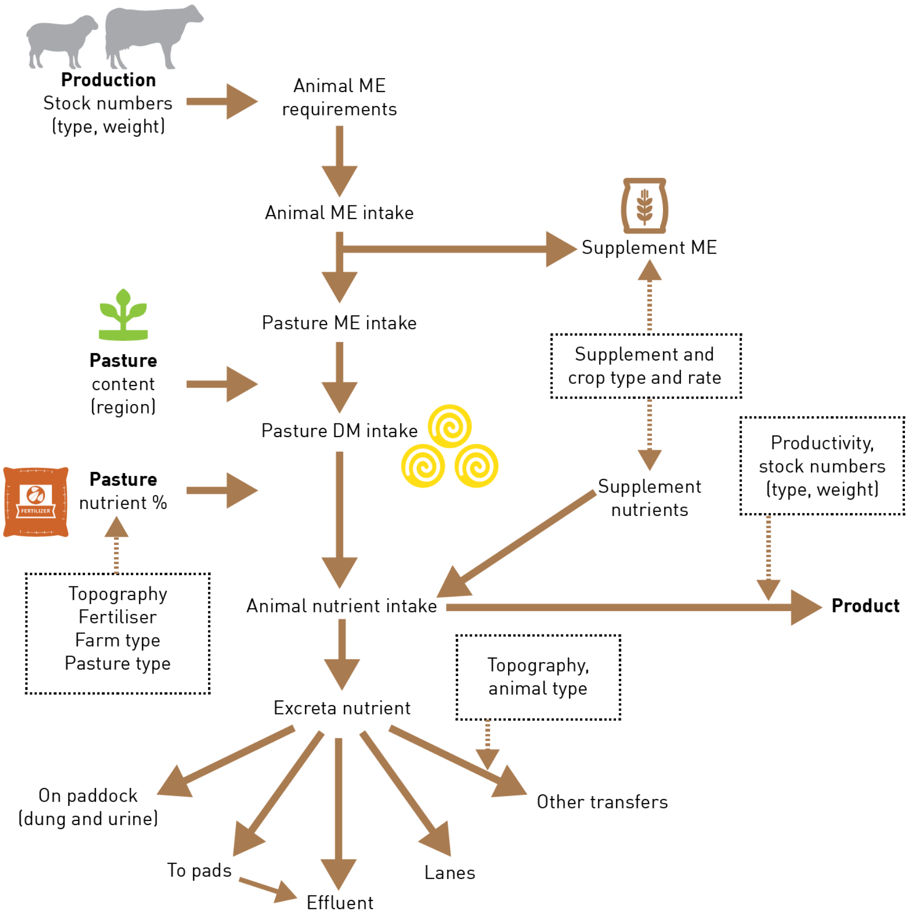

Figure 7.1 Schematic diagram of Overseer animal intake sub-model (Wheeler et al., 2020a)

The approach of having growth as a direct or indirect input to the model is consistent with Overseer's philosophy of the model being "driven" by information that is known or easily obtained by a farmer (see 2.1). It is also consistent with common approaches to nutrient recommendation systems where yield (either likely or hoped for) is an input to the system (Morris *et al*., 2018). This approach has also been used in models underpinning nitrogen recommendation decision support tools (Smith *et al*., 1996; Sela *et al*., 2016). However, it is different to that almost universally adopted for plant growth in contemporary agricultural systems models. In these models, plant growth is an emergent property of climate, soil properties (both constant like texture, and dynamic like water content), and management (e.g., plant variety, dates of planting and harvesting, fertiliser applications, etc.) (e.g., Johnson *et al*., 2003; Johnson *et al.,* 2008; Jones *et al*., 2016; Keating and Thorburn, 2018).

In the following section we will describe in more detail the representation of pasture and crop growth in Overseer, then discuss some of the implications of the approach used.

7.2 PASTURE

As noted above, Overseer, in pasture mode, assumes accurate numbers and production (meat, wool and milk) from one or several animal species and stock classes. It uses these data to predict the ME required to maintain the stock and yield product (Wheeler, 2018b). Pasture data are first required in the form of diet (pasture or supplement) ME content (MJ ME kg^{-1} dry matter (DM)). When combined with ME intake, a value for dry matter intake (DMI) (kg) is derived (Wheeler, 2018a). If pasture nutrient content (e.g., g nutrient kg^{-1} DM) is known or assumed, (Wheeler, 2018i) then it can be combined with DMI to provide total nutrient intake. At this stage the nutrient content of product can be subtracted, and the remainder attributed to nutrient in urine or dung (Wheeler, 2018a) as discussed in Chapter 6.

The Overseer databases for nitrogen, phosphorus, potassium and sulphur are Aotearoa New Zealand-wide and some cover an extended time period (Rajendram *et al*., 2009; Ledgard *et al*., 2002; Litherland and Lambert, 2007; Litherland *et al*., 2002). There are strengths and weaknesses of these sources, especially in relation to Overseer's development. Strengths include the application of standardised cutting techniques and fertiliser application protocols. A weakness is that cutting trials from enclosure sites, especially over one year, lead to pasture composition that differs greatly from the surrounding grazed areas. There is a danger that the soil and pasture composition may reflect the treatment protocols rather than the grazed site characteristics. Detailed analysis would be required to assess whether these strengths and weaknesses affect Overseer estimates.

7.2.1 Estimation of pasture growth

Overseer estimates total annual pasture production from animal productivity. However, the nitrogen model (outside of the urine patch; see Chapter 8) needs estimates of monthly production to estimate pasture nitrogen uptake (Wheeler, 2018l). This uses reference yields for ryegrass and white clover, which are then modified by temperature and plant water availability. To distribute the annual total pasture DM yield across months, the following protocols are used (Wheeler, 2018i):

1. A common response for ryegrass and white clover to soil moisture variation is calculated.
2. The potential maximum yield response (1.2 t DM ha^{-1} per month for white clover, 1.4 t DM ha^{-1} per month for ryegrass) is adjusted for air temperature.
3. Reference yields (1.9 t DM ha^{-1} per month for white clover, 1.2 t DM ha^{-1} per month for ryegrass) are adjusted using the soil moisture and temperature response factors.
4. The adjusted reference yields for clover and ryegrass are combined with their respective sward contents to produce a monthly pasture yields (t DM ha^{-1}).

7.2.2 Estimation of pasture utilisation

Utilisation is the proportion of total pasture grown that is eaten by animals on an annual basis. In Overseer the default values vary depending on the animal type. For dairy, the default is 0. 85, and 0.7 for sheep, beef, and deer. No research data are given for choosing these values (Wheeler, 2018i). It is difficult to get accurate measurements of annual pasture growth and annual DMI, even in a research context, so it is arguably acceptable to use these pragmatic estimates. However, caution is advised. There is wide variation in dairy farm profitability in Aotearoa New Zealand. This suggests the extra feed added in the past 20 years from increased nitrogen fertiliser and imported supplements has not been used to equal effect on different farms (DairyNZ, 2020, DairyNZ Economics Group, 2016). Stocking rates likely have not increased sufficiently to use the extra pasture grown and supplements imported. Supplements are eaten in preference to pasture, so the intake of the latter will fall, leading to decreased utilisation.[20] Very few farmers estimate offered and residual pasture throughout the year, so uneaten pasture often senesces and decays unseen. For example, in a ryegrass monoculture grazed by sheep, Hunt (1983) measured nitrogen return in dead leaves to be 10-20% of the annual nitrogen uptake in herbage. A major contributor to soil organic matter is the leaf litter-decomposer pathway, so any changes in utilisation will affect nitrogen balance.

Pasture utilisation is an emergent property of the system; the amount of pasture utilised is related to animal requirements, availability, quality, and supplementary feed. There is no evidence that we are aware of that suggests that the proportion of pasture utilised is always fixed for a given enterprise, so there is little justification to assume total pasture growth can be calculated from animal performance.

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[20] It is possible to get high pasture utilisation while using high inputs of supplements, but this requires stocking rates that most farmers are not prepared for adopt, often for issues of labour availability or infrastructure constraints such as milking plant capacity.

7.2.3 Pasture ME content and digestibility

Overseer includes the following pasture characteristics: pasture type, pasture ME content, pasture digestibility, clover level, utilisation by animals, and pasture nutrient concentrations (Wheeler, 2018i). Importantly, these characteristics are not independent. For example, a browntop or kikuyu pasture type will almost always be associated with lower ME and nitrogen contents than ryegrass-white clover. The range of characteristics is needed because closely correlated measures may be used to calculate different parameters. For example, although ME and digestibility are highly correlated, the former is central to the estimation of DMI, and the latter to an estimation of faecal output.

Overseer sensibly constrains ME to between 5.8 and 14.8 MJ ME kg^{-1} DM (Wheeler, 2018i). However, Waghorn (2007) notes that ME for Aotearoa New Zealand feed is rarely measured, so will almost always be from feeding tables, or a commercial laboratory. Pasture digestibility, in Overseer, is back calculated from pasture ME content using a conversion equation from Standards for Australian Livestock (1994) (Wheeler, 2018i).

Laboratory feed values are now largely based on Near Infrared Reflectance Spectroscopy (NIRS), a technique that relates spectra from feed samples to chemical analyses by wet chemistry or *in vivo* data (organic matter digestibility (OMD) or ME values). NIRS relies absolutely on high quality reference laboratory or animal metabolism data (Corson *et al*., 1999). These authors give examples for a commercial laboratory where *in vivo* OMD from 35 pasture samples was related to NIRS OMD and then the latter used to predict ME. Pasture silage is difficult to feed as a sole diet, so its OMD was estimated from an *in vitro* cellulase digestibility technique, NIRS spectra measured and ME predicted. For maize silage, wet chemistry acid detergent fibre values were related to spectral analysis and then ME derived. Overseer is critically dependent on accurate ME and OMD values, but the derivation of these values is non-trivial.

Overseer requires pasture ME, digestibility and nutrient content of ingested material. However, the authors acknowledge that this will almost never be available for grazed feed (Wheeler, 2018i). All grazing models will face this limitation, although Johnson *et al*. (2003, 2008; but see Johnson, 2016) calculate digestibility in related to diet composition (protein, fibre, solubles). The diet of grazing animals under best practice management may vary less in digestibility and nitrogen content than the standing pasture they select from. This hypothesis could be tested by using the limited experimental data that exists on selectivity by sheep and cattle grazing pasture.

The default values for ryegrass-white clover pasture ME rely too heavily on Litherland and Lambert (2007). Overseer's predictions of nitrate leaching in animal systems are largely determined by nitrate input from urine, which is, in turn, determined by nitrogen content of DMI (calculated from ME content). Given the importance of ryegrass-white clover pasture in all Aotearoa New Zealand's major animal enterprises, it is essential that ME, nitrogen and digestibility values have some measure(s) of variability associated with them. Overseer's documentation lacks commentary on how this might affect nitrate leaching estimates, although our analysis in 6.1 provides some. An extensive literature review on this topic to provide graphs of seasonal variability for ME, nitrogen and digestibility for different regions and major animal enterprises would inform this commentary.

Lucerne is an important perennial crop in dryland agriculture (150,000 ha of Aotearoa New Zealand; Moot, 2018). It may be used for lamb finishing, conserved hay and for general grazing. It differs from perennial ryegrass in having greater rooting depth and has higher intake potential because of its leaf structure. Its greater rooting depth means that water and nutrients can be drawn from greater depths than are possible for ryegrass-white clover. Note that the use of the 0.6m limit for the calculation of nitrogen leaching is likely not appropriate for lucerne because this plant is capable of accessing both water and nitrogen from much greater depths (Zhang *et al*., 2014); we will address issues of rooting depth further below. The higher intake potential means that stock grazing lucerne will have a higher liveweight gain than those on ryegrass-white clover. However, providing animal production, ME and nitrogen contents are defined or estimated accurately, lucerne DMI should not be biased in comparison with other grazed pastures or crops. Lucerne is a good example of a forage plant that is very important to a group of dryland farmers in the South Island, but it is only a minor contributor to New Zealand's total feed resource. It could not justify the research effort required for ryegrass-white clover. Overseer Ltd has done some work to address deep rooting crops in Overseer. However, the design of the model will make this a complicated exercise, introducing additional parameters and sources of error.

Narrow-leaved plantain (*Plantago lancelota*) and broad-leaved plantain (*Plantago major*) have always existed in Aotearoa New Zealand's exotic pastures as herbal components. A cultivar was bred for agricultural use in the 1990s and recent research has shown its ability to reduce nitrogen leaching and nitrous oxide emissions. This ability has fostered interest in its use where farmers might struggle to meet nitrogen leaching limits from ryegrass-white clover or other pasture alone. A 'plantain module' has been incorporated into Overseer. We understand that Overseer Ltd used a consultative process to generate a scientific consensus on the relationship between plantain content in pasture and nitrogen leaching.

7.2.4 Pasture nutrient concentrations

In Overseer "*Pasture N concentrations can have a significant effect on N leaching via intake. A 10% change in pasture N concentrations can lead to a similar change in N leaching*" (Wheeler, 2018i, p. 8). Overseer requires the nitrogen concentration of pasture on a monthly basis, and on an annual basis for other nutrients. Overseer uses pasture nutrient concentrations to estimate animal nutrient intakes and the amount of nutrient removed from pasture when it is used to make supplements (Wheeler, 2018i). Most experimental studies focus on the nutrient content of material harvested some height above ground level, but grazing ruminants select pasture in both vertical and horizontal planes. Thus, material cut or plucked from pasture may not closely represent that ingested by animals. Selective grazing sometimes allows ruminants to adjust their diet closer to their requirements. However, they do not always have that opportunity. For example, dairy cows on restricted pasture allowance in winter have little opportunity to select because:

1. Pastures are often uniform in height and composition; and
2. Competitive pressure from herd mates means that time spent on selection results in below maintenance DMI.

In contrast, merino wethers recently introduced into a new grazing block containing some legumes can spend time selectively grazing these and ignoring tussock grasses of much lower value. A literature review to determine the extent that selective grazing will lead to ingested nutrient profiles different from those assumed by Overseer should be included in the model documentation.

Overseer assigns an average annual nitrogen concentration of 3.7% to dairy pastures, and 3.3% to sheep/beef farms on flat topography (Wheeler, 2018i). Data are taken from Ledgard *et al*. (2002) and Litherland and Lambert (2007). Several issues were identified in these papers: unequal representation of regions, livestock enterprises, level of nitrogen use, intra-farm sampling, and NIRS versus wet chemistry method. Given the numerous sources of variation and bias it is difficult to see how to determine confidence in a pasture nitrogen concentration value.

Overseer requires monthly pasture nitrogen concentrations, and several sources of Aotearoa New Zealand information show pasture nitrogen concentrations tend to be lower in the October-March period than in winter or early spring. Overseer allows user-defined entry of pasture nitrogen concentration with the proviso that samples must represent samples collected for 4-5 years at six evenly spaced intervals through a year. Wheeler (2018i) recommends that ME content is estimated concurrently.

Where user-defined values are not available, the pasture nitrogen concentrations are modelled using a series of equations that adjust for factors known to affect pasture nitrogen. Overseer sets a base pasture nitrogen concentration of 3.8% for dairy pasture on flat land. This decreases to 3.7% after a soil moisture correction is applied. Pasture nitrogen concentrations are then modelled by adding regional adjustments based on Litherland and Lambert (2007), then adjusted to monthly values using an average curve derived by the same authors. The adjustment factors are complex. They include animal enterprise (dairy, dairy replacement, beef and other); merino pastures; non-ryegrass-white clover pastures; topography (steep, easy hill and rolling); soil moisture; nitrogen fertiliser application rate; clover level and lucerne. In attempting to account for factors that may influence pasture nitrogen concentration, Overseer has developed a complex framework that is difficult to visualise.

A much simpler, alternative approach was considered but rejected because of insufficient data to identify key sources of variation for grass and clover separately. The approach requires knowledge of grass and clover nitrogen concentrations (grassN, $\mathrm{cloverN}$) and proportions in the total pasture ($(1-\mathrm{pclover})$, $\mathrm{pclover}$) to predict:

$$\text{Pasture N concentration} = \mathrm{grassN} \times (1-\mathrm{pclover}) + \mathrm{cloverN} \times \mathrm{pclover}$$

It would be useful for the model documentation to examine the variation within the above and other pasture nitrogen databases to see if the framework can be collapsed to a simpler, but still defensible system of equations. Recently the New Zealand Greenhouse Gas Inventory has collected new pasture samples across Aotearoa New Zealand to reassess nitrogen and ME data. The possibility of using real-time satellite data is also being evaluated. However, the real challenge in implementing this simpler algorithm is in obtaining accurate proportions of grass and clover. This will be even more difficult by satellite than obtaining accurate total pasture mass.

In Overseer, ME and nitrogen content are the key determinants of nitrogen intake. The technical manual suggests that *"To keep relativity between different farms it is important that pasture quality [ME] and pasture nitrogen content [are] commensurate with one another"* (Wheeler, 2018i, p. 27). For grazed pasture, high ME is usually associated with high nitrogen content and vice versa. Errors in estimating nitrogen intake in Overseer will occur if a low nitrogen pasture is attributed a high ME – nitrogen intake will be underestimated. Conversely, if a high nitrogen pasture is attributed low ME – nitrogen intake will be overestimated.

Clover content is based on clover level, with values of very low, low, medium, high and very high – but Wheeler (2018i) does not specify numerical values. Clover content is defined as the annual average clover content (as a proportion of DM) of pasture where fertiliser nitrogen inputs are not applied. The default level for dairy is medium, which is higher than for other animal types. Nitrogen fixation is modelled separately, including the fertiliser-induced reduction in nitrogen fixation. Clover level does not affect nitrogen fixation or denitrification losses directly. Change in nitrogen fixation associated with clover level is balanced by changes in nitrogen immobilisation, but clover level affects nitrogen immobilisation status, so it indirectly affects nitrogen leaching and denitrification rates.

Overseer makes an initial estimate of nitrogen fixation. This estimate has no effect on pasture production or pasture nitrogen concentration and, therefore, no effect on nitrate leaching (see Chapter 8). The nutrient budget approach assumes inputs equal outputs. Any difference between initially estimated inputs (including nitrogen fixation), and outputs is 'balancing error'. To balance the budget the balancing error is allocated to terms within the nutrient budget, including nitrogen fixation. It would be useful if the documentation explained on what basis this allocation occurs and what variation in balancing error is commonly seen. Since the model assumes the farm system is in steady state, all fixed nitrogen (which is initially incorporated into organic matter) must eventually be released as inorganic nitrogen through organic matter decay. Otherwise, the system cannot be in steady state and will always be accumulating soil organic matter if nitrogen fixation is occurring.

7.2.5 Findings

The advantage of using animal production to back-calculate the likely pasture DMI is that a farmer will have very accurate knowledge for milk, meat and wool production from processor receipts, and annual stock number reconciliations. In contrast, the derivation of pasture growth from process-based models will usually require climate, soil nutrients, pasture composition and topography that may be missing or difficult to obtain. Further, a crisis of confidence can occur if a detailed process model fails to predict known annual animal production accurately.

Overseer takes a similarly pragmatic approach with pasture utilisation. Its assumption that pasture utilisation is the same within animal enterprises assumes that farms are equally efficient at using pasture grown. The wide variability in dairy farm profitability suggests that stocking rates have not always increased sufficiently to take advantage of the extra supplements imported or the extra pasture grown from increased nitrogen fertiliser applications. This challenges the idea that farmers manage their stocking rates or supplement management to a utilisation goal, which Overseer would assume they do when being used for scenario modelling. Assuming utilisation to be constant across farms also ignores a potential effect on the nitrogen balance, as uneaten pasture will contribute to soil organic matter.

The calculation of pasture ME and nutrient content is critical to determining nitrogen leaching in animal systems. There are concerns about how pasture ME values were calculated, and how those lab values would relate to what is ingested by livestock given diet selectivity. Diet selectivity has a similar effect on estimates of pasture nutrient content; the nutrient content of the pasture is not the same as the nutrient content of the pasture consumed. Furthermore, Overseer's approach to estimating pasture nutrient content is complicated; a simpler alternative may be more transparent and equally accurate.

Overseer's pasture modelling is important to the estimation of nutrient losses from livestock systems. To have confidence in this component of the model, further analysis and evidence should be included in the technical manuals to demonstrate the materiality or otherwise of the concerns noted above.

7.3 CROPS

7.3.1 Introduction

The crop model calculates crop growth directly from the user-defined yield (i.e. the growth that would have occurred to obtain that yield), in contrast to the approach for pasture, which is based on animal production and influenced by supplementary feed supplied. The Overseer crop model is designed to provide the long-term annual average of nitrate leaching from any user-defined cropping rotation. It has been parameterised based on process-based model simulations for typical farm systems and environments of Aotearoa New Zealand (Cichota *et al*., 2010) and is intended to be simple enough to be used by people with a low to medium level of modelling expertise, such as farmers and regional council staff (Cichota *et al*., 2010; Wheeler, 2018l).

Leaching is the loss of nitrate beyond the effective base of the root zone. In Overseer, leaching is defined as the nitrate percolating below 0.6m depth each month, and it is assumed there is no nitrogen uptake below 0.6m. Conversely, for crops the hydrology model calculates the crop water uptake in the water balance in the top 1.5m. This is the assumed maximum rooting depth of most crops grown in Aotearoa New Zealand (Cichota *et al*., 2010*)*. Nitrate leaching is discussed in Chapter 8, but note here that crop growth affects leaching through its effect on both soil water and nitrogen.

The rotation (e.g., crop, yield, management information such as sowing date) being assessed is specified by the user. However, the management of the block prior to the assessment affects soil nitrogen during the time of the rotation being assessed. The user needs to enter information on the block's history, such as the rotation in the previous year and the proportion of the ten years prior to the assessment that the block was in pasture (Wheeler, 2018l).

The main purpose of this section is to describe how crop growth is represented in Overseer. However, given that an important purpose of the crop model is the estimate of nitrate leaching, it is useful to outline the attributes that go into the calculation of nitrate leaching and highlight which of these are affected by crops. Details on many of the processes that go into the calculation of nitrate leaching are given in Chapter 8.

7.3.2 Crops and the hydrology model

The hydrology model for crops is a simple single-layer water balance model to determine water available to the crop (Wheeler, 2018o). The soil is assumed to be homogeneous down to the bottom of the rootzone where drainage occurs. The user specifies the appropriate soil type and the depth of the impeded layer. Data come from S-map where available and the Land Resource Inventory where not. Farm soil testing results can also be entered.

The hydrology model runs on a daily time-step. The daily water balance is calculated over two years, to allow calculation of the effects of the previous rotation on the soil's nitrogen status during the rotation being assessed (as outlined below). Note, as described in Chapter 5 and 7.1, other processes in the model run on a monthly time-step. Where soil water interacts with these processes, the results of the daily water balance are summed to monthly.

The soil water balance is the difference between water input to and losses from the soil. Water inputs come from rainfall and irrigation (less runoff). Losses are from drainage (below depth of the soil profile and/or through mole-tile of field drainage networks), evaporation from the soil, and transpiration by the crop. Transpiration each day is the product of potential evapotranspiration (input from the climate file), crop cover (from the crop growth model) and a factor that reduces transpiration as the soil dries. Thus, crop cover is the main factor linking the crop model to the soil water model.

7.3.3 The soil nitrogen model

The soil nitrogen model calculates the mineral nitrogen available for leaching in a month, which, as described above, is one of two determinants of nitrate leaching. The crop rotation, which is specified by the user, determines relevant parameters in the nitrogen model, such as the nitrogen removed through harvested product and the nitrogen remaining in the soils and residues and roots (Cichota *et al*., 2010). As described above, the nitrogen balance is calculated over two years: the year being assessed and the year prior to the assessment. Information on the previous year is important because of nitrogen in residues and roots from the previous rotation. Longer-term land use, specifically time under pastoral use, also affects nitrogen cycling in the rotation being assessed, as described below (Wheeler, 2018h).

Mineral nitrogen in each month is calculated as the difference between additions to and removals from the soil mineral nitrogen pool. Additions to the pool come from (Cichota *et al.*, 2010):

- Applications of nitrogen in fertiliser (mineral or organic), effluent, irrigation water, or rainfall; and
- Mineralisation of nitrogen in residues and roots from the rotation in the previous year. This is affected by:
    - The time the block has been under pasture in the previous ten years;
    - The time since cultivation; and
    - The soil environment (e.g., soil water and temperature).

Removals from the soil mineral nitrogen "pool" include (Cichota *et al.*, 2010):

- Losses to the environment through volatilisation, denitrification and leaching (below 0.6m depth); and
- Nitrogen taken up by the crop.

Soil organic matter is assumed to be constant through time (i.e. in steady state) so mineralisation of nitrogen from soil organic matter rundown is not included in the model. Nor is immobilisation of mineral nitrogen, if soil organic matter is increasing over time at the site (Wheeler, 2018h). However, it should be noted that immobilisation of nitrogen is included in the urine patch model for pasture systems – this is discussed in Chapter 8.

If removals of nitrogen exceed additions, the amount of nitrogen in the soil mineral nitrogen pool is decreased. It is possible for calculated removals to exceed the sum of both additions and the soil mineral nitrogen pool. This results in a negative amount of soil mineral nitrogen. This is physically impossible. This situation is indicated to the user via a 'nitrogen deficit' in the model output. A deficit could occur if the crop nitrogen uptake is too high for the specified nitrogen supply or the amount of fertiliser applied is lower than the amount that would have had to be applied for the rotation and soil conditions specified. The existence of a "nitrogen deficit" flags to the user the need to re-examine the specification of the analysis (Cichota *et al.*, 2010).

There are several ways in which crops influence the nitrogen cycle in Overseer:

- They take up (remove) mineral nitrogen from the soil as they grow;
- They leave residues and roots in the soil, which release nitrogen as they mineralise; and
- Transpiration from crops affects soil water which influences nitrogen mineralisation.

In the first two points, the effect of the crop on the nitrogen cycle is direct. In the third it is indirect.

Nitrogen taken up by the crop is determined by the crop biomass accumulated each month and the nitrogen content of that biomass. The nitrogen content of crop biomass, residues and roots are crop-specific constants in the model, i.e. they are not user inputs (Wheeler, 2018h, Table 6).

7.3.4 Annual crops

Crop growth in Overseer is based on the details of the rotation (e.g., crop, yield, management information such as sowing date) specified by the user. It is assumed all crops are under GMPs. The outputs from the model are (Cichota *et al.*, 2010):

1. The mass and nitrogen content of the crop residues and roots left and harvest;
2. Nitrogen uptake from the soil (each month); and
3. Crop ground cover.

The first two groups of output variables need to be back calculated from yield using allometric relationships and constants for the specified crop as well as assumptions. The calculation of crop ground cover is done separately.

Aboveground biomass at harvest is required for calculating the mass of the crop residues and roots, as well as monthly nitrogen uptake. Biomass is calculated from yield and harvest index, which is the proportion of above ground biomass that is harvested product (Biomass = Yield / Harvest index). Harvest index is a constant for the crop type. Residues are the difference between biomass and yield. The mass of roots is a proportion of biomass. The nitrogen concentration of residues and roots are constants for the specified crop (Cichota *et al.*, 2010).

Monthly nitrogen uptake is back calculated from biomass assuming that nitrogen uptake is directly related to the increase in biomass in each month; and that the increase in biomass over the crop's life follows a sigmoidal function (Figure 7.2). The crop's life is represented in thermal time (growing degree days, °C d). The amount of nitrogen taken up from the soil in a month is the same as the increase in nitrogen in the crop biomass, which is based on nitrogen concentrations in the different components of biomass (e.g., leaf, stalk, harvested produce). These concentrations are constants for the crop type (Cichota *et al.*, 2010).

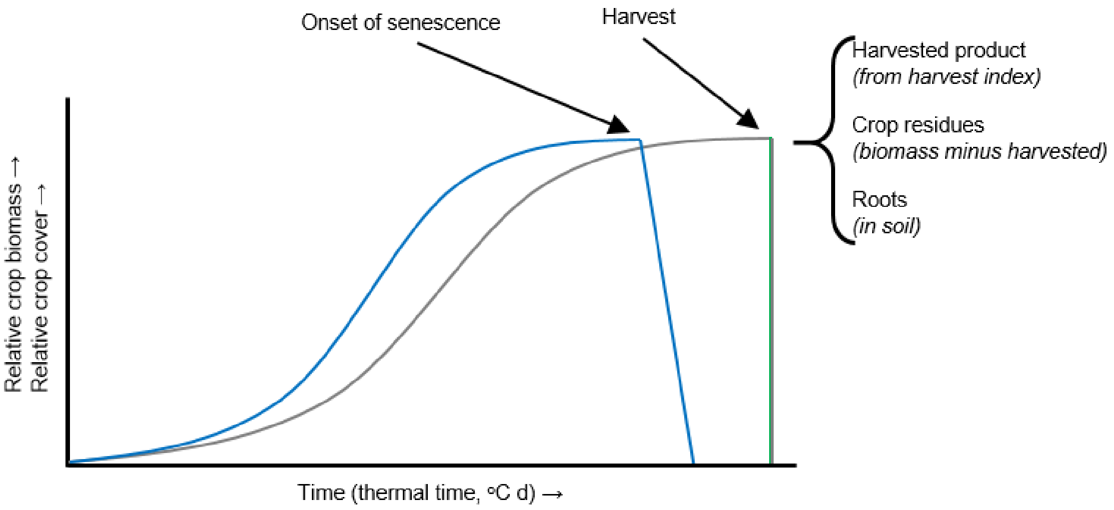

Figure 7.2 Schematic representation of the variation in (thermal) time of relative biomass (green) and crop cover (blue) used in the Overseer crop model (after Cichota et al., 2010)

Crop ground cover is needed to calculate transpiration, a term in the soil water balance. Ground cover is assumed to be complete (i.e.100%) when the crop's canopy is closed. The thermal time to achieve canopy closure is a constant for a crop type. The change in cover between planting and canopy closure is calculated assuming that cover increases from no cover at planting to complete cover following a sigmoidal pattern (Figure 7.2). In some crops the canopy senesces from the time the crop reaches maturity and cover decreases. The thermal time at which senescence occurs is a constant for a crop type, and cover decreases linearly after that.

There are many constants in the Overseer crop model. Some of these are well established in the literature, such as the nitrogen concentration of the biomass of different crops and harvest index. Others were developed by calibrating the relevant constant in Overseer against crop rotations (or bare soil) simulated with the land use change and intensification (LUCI) model (Jamieson *et al.*, 2006; Zyskowski *et al.*, 2007).[21] Calibrating Overseer against the output of another model was done because the small number of nitrate leaching field studies do not cover an adequate range of environments in Aotearoa New Zealand (Cichota *et al.*, 2010).

7.3.5 Perennial crops

The representation of perennial tree and vine crops (i.e. kiwifruit, apples, grapes, avocados and peaches) in Overseer generally follows the approach used for crops, outlined above. These crops persist through time so nitrogen uptake from the soil occurs through fruit growth, regrowth or previously pruned wood, and any growth in the tree's frame, rather than the whole plant biomass. The yield of harvested fruit is entered by the user. Nitrogen in leaves that senesce and wood that is pruned

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[21] There are multiple tools and models which use the LUCI acronym. In this report, LUCI refers to the land use change and intensification model developed by Plant and Food Research. There is another well-known model called LUCI, which is the Land Use Capability Indicator tool (see LUCI, 2018).

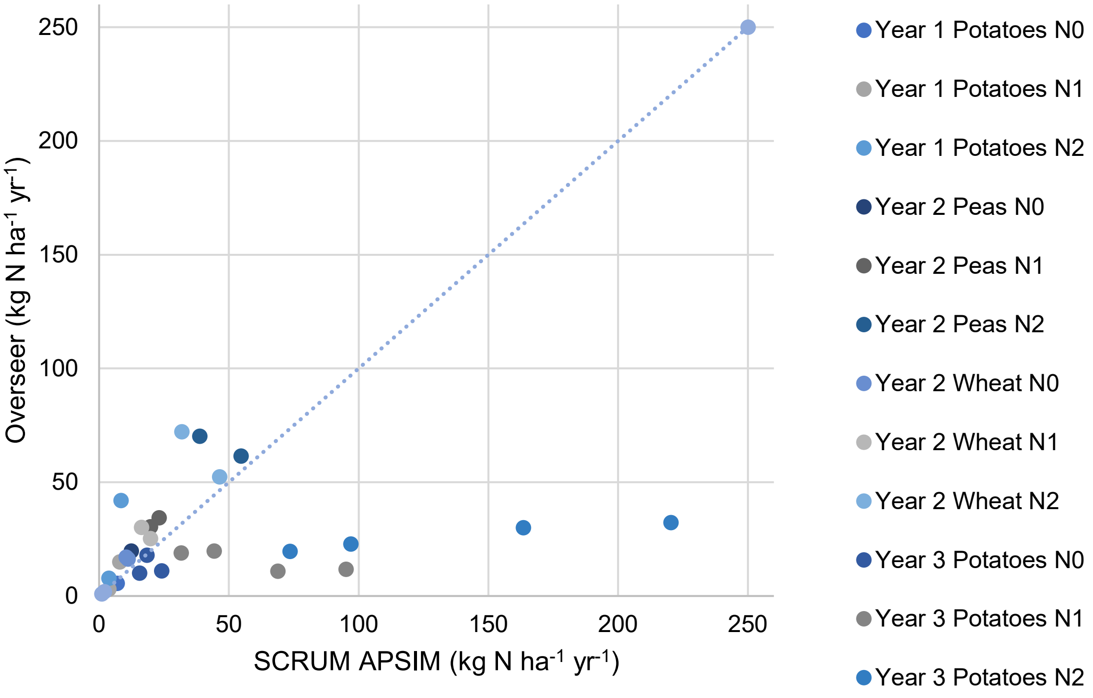
is returned to the soil through mineralisation, as happens with residues of annual crops. Most of the parameters that control nitrogen uptake (e.g., fruit nitrogen concentrations) and mineralisation are specified in the models. Some of these are specified for the crop type (e.g., fruit nitrogen concentrations) and others have a temporal dimension so are specified for each crop and month. The same is true for ground cover (an input to the hydrology model) (Wheeler, 2018h).

There can be pasture under and between trees, with the water and nitrogen dynamics of the pasture represented in the same way as described above (Wheeler, 2018h).

7.3.6 Performance of the crop model

As noted in 7.3.1, the Overseer crop model was designed to produce long-term annual average nitrate leaching from any user-defined cropping rotation. There have been two publicly available studies of the performance of the model in that context (Cichota *et al*., 2010; Khaembah and Brown, 2016). These studies tested the Overseer crop model's predictions of nitrate leaching against measured data from one experiment and simulated results from more complex models, the assumption being that the more complex models represent "reality" with enough accuracy to provide a useful test of Overseer. The models (LUCI and APSIM-SCRUM), were parameterised against experimental data prior to simulating the rotation scenarios against which Overseer was compared.

In initial testing, Overseer calculations of nitrate leaching and drainage compared well with those from the LUCI model output (Cichota *et al.,* 2010). In subsequent testing against measured data (Cichota *et al.,* 2010) or output from APSIM-SCRUM (Figure 7.3a-b, Khaembah and Brown, 2016) agreement was poorer with an overall tendency for Overseer to underpredict nitrate leaching. There were also specific situations with substantial overprediction. The general underestimates compared with the APSIM-SCRUM output resulted from a higher crop nitrogen uptake and denitrification in Overseer. The general underestimates compared with measured data were caused by an underprediction of drainage (because of overprediction of evapotranspiration) (Cichota *et al*., 2010). Addressing this problem would require work to Overseer's soil water modelling (see Chapter 8).



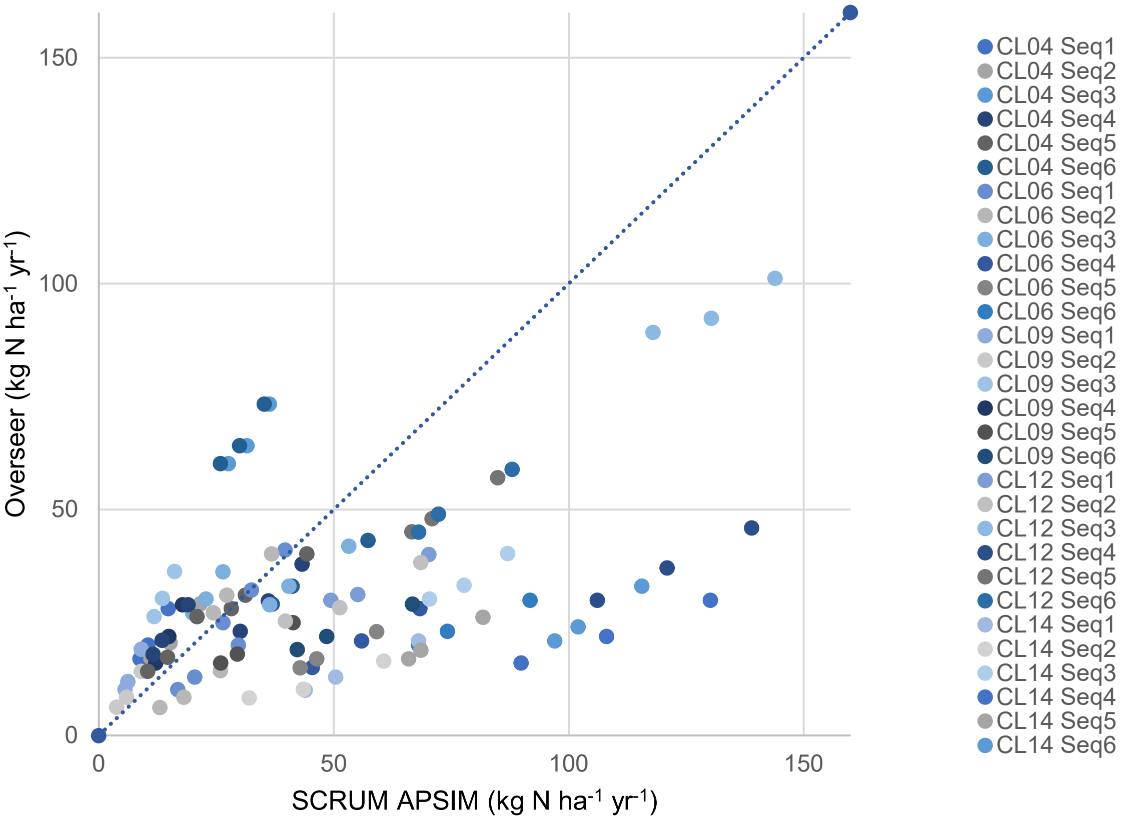


Figure 7.3 Comparison of nitrogen leaching from the Overseer crop model with outputs from the APSIM-SCRUM model for two different rotation specifications, adapted from Khaembah and Brown (2015).
a) shows comparison between nitrogen leaching estimates estimated by Overseer and SCRUM-APSIM relative to the 1:1 reference line. Estimates are based on two crop sequences (potatoes-peas-potatoes and potatoes-wheat-potatoes), two irrigation rates (optimum and excess) and there fertiliser nitrogen rates (N0 = no added fertiliser, N1 = optimum (recommended rate) and N2 = excess (twice the amount applied in N1).
b) shows comparison between nitrogen leaching estimates estimated by Overseer and SCRUM-APSIM relative to the 1:1 reference line. Estimates are across sites and crop sequences. Overall, there was poor agreement between the two models.

7.3.7 Discussion

As discussed in 7.1, Overseer does not use biophysical models to predict yield, but has yield as a user input. It is probably a reasonable assumption that farmers know their crop yields, although growers' definitions on yields can vary (Bloomer *et al*., 2020). Overseer then uses constant parameters to control plant organ growth, allocate residues (e.g., through harvest index) and roots, the timing of residue additions and prunings, and then generate mineralised nitrogen from the residues and roots, which have an assumed nitrogen and carbon content. The constant value of these parameters is problematic, because plant tissue nitrogen concentrations can vary between sites and seasons, in response to, for example, climate or soil nitrogen supply (the dynamics of which are not represented in the model – see Chapter 8).The dynamic nature of plant tissue nitrogen concentrations can be modelled as the balance between the supply of, and demand for, nitrogen in different tissues or organs (e.g., Brown *et al*., 2014).

It is difficult, in general, to model multiple short-term vegetable crops per year. In practice, vegetable growers using Overseer have had to set up large numbers of blocks (for example, hundreds of blocks ranging in size from 0.1-1 hectare; Bloomer *et al*., 2020) to reflect their farming system accurately. The user interface is not practical for vegetable growing due to the complexity of their rotations (see Figure 7.4) and Overseer's monthly time-step and user interface. As described above, Overseer considers cropping after a period in pasture; this rotation is common practice in commercial vegetable production.

Features of Overseer can also mean that when commercial vegetable growers follow best practice, they get unexpected results in Overseer. One such feature is the monthly time-step. Best practice fertiliser application is to split fertiliser applications monthly, so they match crop demands. However, when this is inputted into Overseer it results in higher nitrogen losses (Bloomer *et al.,* 2020). Bloomer *et al*. (2020) hypothesised that this was due to Overseer having a monthly time-step and, therefore, predicting that nitrogen uptake was complete by the time additional fertiliser was applied meaning additional fertiliser went unused, when actually the plants were still actively growing.

Figure 7.4 Representation of arable and commercial vegetable rotations. From Norris et al.*,* 2017

Another feature also related to nutrient uptake. Best practice is for growers to plant cover crops in ground that would otherwise be bare in winter. Some growers plant an annual ryegrass, either for grazing or to incorporate the grass residues into the soil to build soil organic matter. However, when this was entered into Overseer, it estimated very higher plant uptake of nitrogen followed by rapid mineralisation and high nitrogen losses the following year. The authors felt that this was a large overestimation (Bloomer *et al*., 2020).

Another issue is the modelling of residues from deciduous trees and vines that are also pruned. Field observations using buried fluxmeters (Green *et al*., 2006) have shown higher nitrate leaching immediately after leaf-drop and pruning resulting from the mineralisation of nitrogen from these residues during the wet winter period. It is unclear how residues of horticultural crops are calculated. Presumably Overseer accounts for fruit-thinning, leaf-fall and seasonal pruning.

A serious limitation is that the depths used to calculate nitrogen leaching (0.6m) and crop water uptake (in some cases up to 1.5m) are different. 0.6m is very shallow for many perennial trees and vines; there is a lot of nitrogen uptake below 0.6m, and water uptake below 1.5m. There are many published accounts of deep-water uptake by trees and vines down to beyond two metres (Green *et al*., 2006). In such circumstances, the deep soil can dry down in summer, and it might not re-wet to permit drainage until August-September (Figure 7.5; from Figure 3 of Green *et al*., 2006). The soil water content and drainage behaviour of this deep root zone could not be modelled by only considering a depth of 0.6m.

For kiwifruit on the deep volcanic soils on the Bay of Plenty, roots have been found down to 9m (Holmes *et al*., 2015). The amount of water draining at 0.6m will be much greater than that draining at the base of the root zone of deep-rooted trees and vines. It is clear from Figure 7.5 that soil water content varies considerably through the soil profile.

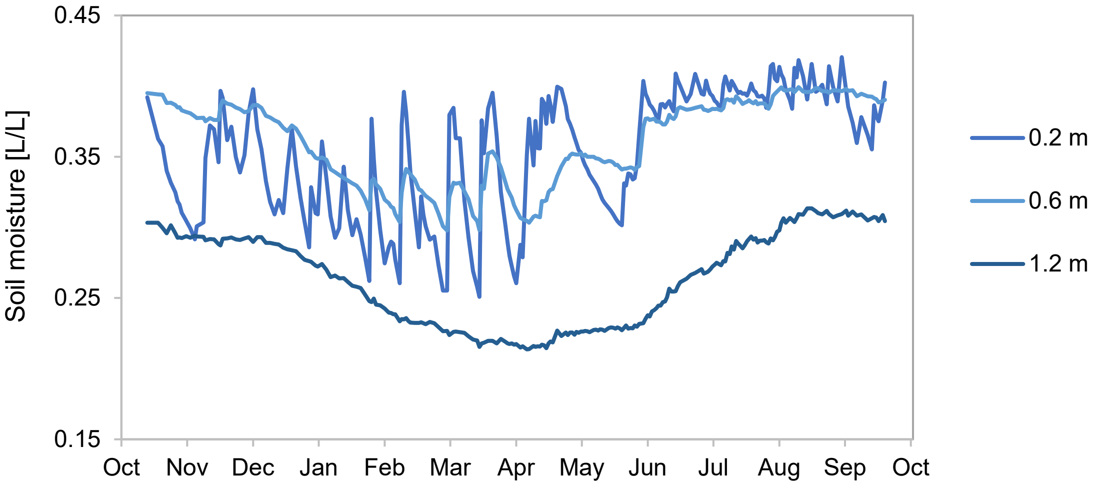


Figure 7.5 The seasonal pattern of soil-water content at different depths of the root zone in kiwifruit measured by time domain reflectometer probes. The traces are for the depths 0.2, 0.6 and 1.2m. Figured adapted from Green et al. (2006).

Field measurements using tension fluxmeters (Green *et al*., 2010) are being used in Aotearoa New Zealand across a wide range of land-uses to monitor nitrate leaching. These are currently being used under a deep-rooted horticultural crop to assess the amount of nitrate leaching at both 0.6m and 1.2m. Not surprisingly, the leachate load at 0.6m is being found to greater than that at 1.2m, as there is obviously plant uptake of nitrogen between 0.6m and 1.2m. There is also likely to be some denitrification in that deeper zone. This challenges Overseer's assumption that nitrate uptake does not occur below 0.6m.

In Overseer irrigation considers the 1.5m rootzone for deep-rooted crops. This is not appropriate for deep-rooted trees and vines, as there is a far greater store of water in the deeper root zone. Most horticultural crops are irrigated by drip or mini-sprinklers. It is unclear how the wetted drip spots interact with the rest of the orchard system. It is interesting that urine patches in grazed pastures are handled separately in Overseer (see 8.3), and yet the effect of the dripper zones on drainage and leaching seems to be averaged spatially. Overseer's modelling of irrigation from drippers and mini-sprinklers does not seem to accord with current practices. It seems the maximum drip irrigation options are 65mm per application with a seven-day return period, but drippers would struggle to apply 65mm in an application. The minimum application is 10mm, with a five-day return period. Drippers have the same default Overseer settings as 'solid set' irrigation. In general, drip irrigation is either by a 'flick-of-a switch', or more commonly under computer control. It is used tactically, especially early in the season if drought threatens flowering, and it is generally reduced late in the season to curtail vegetative vigour, and to promote fruit maturation.

7.3.8 Findings

Overseer operates in such a way that for a given set of inputs, leaching will be constant for the whole year or for each month. In doing so, it overlooks the management, biophysical and climatic factors that drive the variability in nitrate leaching through time (within a year, and year-to-year). This approach is not reasonable because:

- Yield, and thus crop nitrogen uptake, will not be constant from year to year. This variation will drive variation in nitrate leaching which will not be accurately reflected with Overseer's quasi-equilibrium steady state approach;
- Even for the same yield, crop nitrogen uptake will not be constant (because plant tissue nitrogen concentrations can vary between sites and seasons in response to climate and nitrogen supply; e.g., Loomis, 1997);
- Even for the same yield, crop nitrogen supply (from mineralised organic components in the soil) will change and fertiliser added may change. For example, there will be less mineralisation in cold years. The model doesn't include soil organic carbon, which can involve significant fluxes of soil inorganic nitrogen through mineralisation and immobilisation. This is discussed in Chapter 8;
- There will be significant interactions between the timing of events such as tillage, sowing, fertiliser additions, plus harvesting, and the timing of local weather events, especially rainfall. There will be large variation in nitrate leaching between months and between years; and
- Overlooking variability overlooks short-term changes within Papatūānuku which provides particularly important information for kaitiaki.

The justification for treating nitrate leaching in a constant manner is that the calculated constant will be a close approximation of the long-term average. There is, however, not a lot of evidence to support that conclusion (Khaembah and Brown, 2016). The non-linear nature of nitrate leaching and the assumed premise that leaching is a linear process means this result is not surprising. Further, the approach taken means that the model cannot account for external factors that influence average nitrate leaching (e.g., above- or below-best practice management, trends in soil organic matter).

There are terms in the model ("balancing error" in the pasture model (7.2.4) and "nitrogen deficit" in the crop nitrogen model (7.3.3)) that are included because the model does not conserve mass. These terms correct the *numerical* inequality coming from lack of mass balance, but do not restore mass balance in the formal sense of the process. Nitrogen supply to the crop and nitrogen uptake by the crop are not connected, yet the latter must be limited by the former. This limitation in Overseer was identified as a likely reason for the poor performance of Overseer when tested against APSIM-SCRUM (Khaembah and Brown 2016).

The model cannot account for changes in soil organic matter through time. This is a limitation. For example, land management practices that increase soil organic matter tend to reduce nitrate leaching losses. The reverse is true for soil organic matter depletion (e.g., when arable cropping systems replace long-term pastures). Similarly, composts used in horticulture to improve soil structure would also affect soil organic matter dynamics and, therefore, nitrate leaching losses.

Overseer overlooks some important soil (e.g., variations in soil with depths, deep cracks) and crop (rooting depth) factors that will affect leaching at different sites and crops (e.g., deep-rooted perennials). There are several limitations for Overseer's modelling of horticulture and commercial vegetables. It does not model short-term vegetable rotations well. It seems not to consider residues and prunings from deciduous trees and vines. The roots of some perennials extend deeper than Overseer models, and processes at those depths will affect nitrogen dynamics. Overseer's irrigation set-up also does not reflect the reality of horticultural production.

Despite the analytical engine of Overseer being relatively simple in structure, through subsequent developments Overseer has had complex, biophysical and geohydrological sub-models added on to handle a wide range of new farm and orchard practices and activities (e.g., urine patches, hydrology, and the crop nitrogen model and residues (Wheeler *et al*., 2020a)). It seems that these additional, and complex sub-models are very difficult to parameterise, such that in most cases, the complex sub-models run using default values thus limiting the benefit that could potentially be gained from the additional complexity.

The justification for the simplified approach of the base analytical engine is to increase usability to make the model accessible to a wide use base (as discussed in 2.1). We think this simplification could be achieved by having a model that better represents our understanding of the processes that determine nitrate leaching in cropping systems (which traditionally is likely to be complex to use) combined with tools to simplify its use. Examples of such systems exist (e.g., YieldProphet[22], Hochman *et al.*, 2009). Two research questions arise from this finding: to what extent are the predictions from the detailed and complex sub-model compromised by being run through a simplified annual average front end? How do predictions from a fully mechanistic model compare with Overseer? An example of the exploration of the second question exists in the report by Khaembah and Brown (2016). The answer is 'not that well'.

7.4 CONCLUSION

Pastures and crops take up water and nutrients, including nitrogen. They therefore directly affect the nitrogen cycle, including losses of nitrogen via nitrate leaching, denitrification, etc. Thus, the representation of plant growth has a direct bearing on the calculation of a farm's environmental nitrate leaching losses. We support the need for a relatively user-friendly farmer/grower interface. However, if modelled plant growth or production behind the interface is simplified to the point that it is significantly different to that which happens on the farm, then the modelled environmental nitrate leaching losses will be significantly different to actual losses. Based on the findings outlined above, we do not have confidence in Overseer's outputs from modelling cropping, horticultural, or commercial vegetable enterprises.

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[22] www.yieldprophet.com.au

8 Soil water and nutrient dynamics

Understanding Overseer's treatment of soil water and nutrient dynamics is necessary to assess its overall fitness for purpose in the context of its use in regulation and as a decision support tool, since these dynamics are imported to modelling nutrient losses. Soil water and nutrient dynamics determine nutrient losses (either through leaching or runoff) of pasture and crop systems. Furthermore, nutrient dynamics are closely related to, and influenced by, soil water dynamics. As described earlier, farmlet trials used to calibrate and test Overseer have been biased towards nitrate loss and do not appear to account for surface hydrological pathways for which organic and ammoniacal forms of nitrogen are important.

There is no single, cohesive, description of the nitrogen dynamics; it is spread around various chapters (Wheeler & Watkins, 2018a; Wheeler, 2018o). Similarly, it is challenging to identify precisely how phosphorus dynamics are treated, particularly leaching and surface runoff. Overseer makes some core assumptions in its hydrology and nutrient modelling. It assumes all soil water and nutrient movement calculations through the soil profile are based on single layers:

- The 0-0.1m profile is used to calculate soil evaporation;
- The 0-0.6m profile is used for transpiration in pastures, nitrogen uptake in pastures and crops, and leaching; and
- The 0-1.5m profile is used for transpiration in some crops.

These different soil layers are not connected in calculations but are treated separately (Wheeler, 2018o).

8.1 HYDROLOGY

The soil water, or hydrology, model includes the basic components of inputs from rainfall or irrigation, runoff, evapotranspiration (soil evaporation and plant transpiration), infiltration and deep drainage (Wheeler, 2018o). These processes can be episodic. For example, runoff may only occur for intense rainfall periods over a short period of time during any day. Similarly, deep drainage may lag rainfall and start with an initial pulse of drained water that may taper off quite quickly. Despite runoff being modelled, surface forms of nitrogen exported by this important hydrological pathway are not quantified by Overseer (see 5.3).

While most other aspects of the model use a monthly timestep, the hydrology components have a daily timestep, using daily rainfall input data. However, as with the rest of the model, rainfall inputs are not actual data, but are derived from location characteristics as discussed in 5.1. Once the hydrology component has been run, monthly averages of runoff and drainage are calculated, along with the average soil water content. The last of these is then used with the plant model (crop or pasture) and evapotranspiration is then calculated, although this can lead to difficulties if evapotranspiration exceeds available water – this is discussed below (Wheeler, 2018o).

8.1.1 The soil water balance model

The soil water balance model is based on Porteous *et al.* (1994), which is presented as a simple single-layer model designed for soil water dynamics under pasture systems. In that paper, the authors concluded that the 'Veihmeyer' model, where evapotranspiration is independent of actual soil water content until the soil reaches wilting point, performed well for soils of depth 0.5 or 0.7m. This is inconsistent since, by definition, transpiration will decline to zero as soil water content approaches wilting point. Porteous *et al.* (1994) also only considered level pasture sites and assumed that runoff only occurs when soil water content exceeds field capacity and rainfall exceeds evapotranspiration. It is not our aim to review the Porteous *et al.* model in detail, other than to note that it appears that Overseer uses a single layer water balance model but treats other aspects of the hydrology in different ways. For examples, it includes reductions in both transpiration and evaporation in relation to soil water content as the soil dries.

Overseer models three soil profile layers separately: 0-0.1m for evaporation and runoff calculations, 0-0.6m for nitrate leaching and pasture transpiration, 0-1.5m for crop transpiration. These layers are not connected. The top 0.1m layer is used to calculate soil water evaporation and surface runoff. Water available for evaporation is calculated as the soil water content in excess of wilting point in this layer. Actual evaporation is then related to potential evapotranspiration and ground cover as calculated by the plant (pasture or crop) component. There is a minimum potential soil evaporation rate of 10% to allow for possible upward movement of water in the soil through capillary action. The top 0.1m layer also includes a transpiration loss that is 1.4 times that of transpiration at 0.6m depth (due to the greater root density in shallow soil). The 0-0.6m layer is modelled independently. It appears that this uses runoff calculations from the top 0.1m. The 0-0.6m layer is used for calculating nitrate leaching. The 0-1.5m layer is modelled as for 0-0.6m but is only used in transpiration of crops (Wheeler, 2018o).

Soil water distribution is well-known to vary through the soil profile depth – there are many illustrations of this in the literature, for example Freebairn *et al.* (2009). At a mechanistic level, the most widely accepted model for soil water infiltration is the Richards' equation (Richards, 1931) which combines Darcy's law (Darcy, 1856) with mass balance. The Richards' equation is a highly non-linear partial differential equation and requires relationships between both soil matric potential and hydraulic conductivity with volumetric soil water content. Despite this complexity, it is an important starting point for the study of soil hydrology. Darcy's law states that water moves along a water potential gradient (first published by Henry Darcy (1803-1858) in 1856). This captures the underlying physical process of water movement. Solving the Richards' equation involves complex numerical analysis which is why simpler approaches are generally used. However, it illustrates the importance of incorporating variation in water content through the soil profile in overall dynamics.

While simpler approaches to the Richards' equation are often used in agricultural models, these almost universally involve multiple layers to capture the distribution of water through the soil profile (e.g., Johnson *et al*., 2008) as it varies with time. Using multiple soil layers means that the change in soil water, organic matter, and inorganic nutrients through the soil profile can be modelled. For example, water and nutrients can exhibit a pulse through the profile depth through time. These distributions can be important factors in processes like nitrate leaching. If there is a higher concentration of inorganic nitrogen near the soil surface compared with at 0.6m depth, the potential for leaching may be different. Since Overseer uses a single soil layer, it is unable to capture these types of behaviours. Using a multi-layer soil model requires no more inputs than a single layer model since the same soil hydrological characteristics can be used through the soil profile.

A more rigorous hydrology model would be a multi-layer model that allows versatile definitions of soil characteristics through depth, which may be required, for example, for duplex soils[23], or loess overlying outwash gravels which are common in parts of New Zealand. It would require actual climate inputs, particularly rainfall. This would not preclude aggregating output values to monthly for reporting.

8.1.2 Landscape considerations

The discussion has so far focussed on a single paddock approach to modelling soil hydrology. It has not addressed spatial characteristics of a farm in relation to water and nutrient transfers. Research both nationally and internationally notes that spatial variation in landscape characteristics, hereafter 'attributes', such as topography, soil physical and chemical characteristics, may account for a significant component of the spatial variability in water quality relative to land use on its own (Johnson *et al*., 1997; Thomas *et al*., 1999; Snelder and Biggs, 2002; Hale *et al*., 2004; King *et al*., 2005; Kratzer *et al*., 2006; Hume *et al*., 2007; Becker *et al*., 2014). For example, soils with a moderate to high infiltration rate that are also well drained are less prone to runoff than soils with a low infiltration rate and/or that are imperfectly to poorly drained. In the former setting, deep percolation of water through the soil profile maximises the attenuation of nutrients and microbes by the soil matrix and deeper unsaturated zone. In the case of low infiltration rate and imperfectly to poorly drained soils, a greater proportion of contaminants are likely to leave the property as surface runoff or through artificial subsurface drainage with less opportunity for attenuation by the soil matrix (see Monaghan and Smith, 2004). Accordingly, the type and severity of losses from farm should be expected to vary as landscape attributes vary and with the degree to which land use has modified natural soil drainage.

The important role of landscape attributes over the magnitude and severity of water quality issues is especially important for geologically diverse landscapes such as New Zealand (Close and Davies-Colley, 1990; Johnson *et al*., 1997; Hughes *et al*., 2016; Wu and Lu, 2019). Here, small-scale changes in topography and soil properties can equate to significant differences in the type and magnitude of contaminants lost from farm. For example, nitrate is only likely to be the sole or dominant form of nitrogen lost from farm under a restricted set of landscape attributes (as discussed in 5.2), specifically:

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[23] Duplex soils have contrasting textures between soil horizons, for example where the top 0.2m is a sandy clay loam while below that is clay.

- Flat land (low slope < 2-4°) across varying landscape scales (decametres to kilometres) and forms (hill country[24], lowland, high altitude plateaus);
- Soils with moderate to high infiltration rates; and
- Soils that are well-drained.

The area of productive land that meets these criteria in Aotearoa New Zealand is less than 20%. Outside of this range of landscape attributes, there is a greater likelihood that other hydrological pathways and forms of nitrogen will be lost from the farm. In some settings, these different forms of nitrogen may make up a significant or even the dominant proportion of the total nitrogen lost (see 5.3). Notably, these different forms of nitrogen are no less critical in terms of their potential effect on water quality.

Using a landscape context, land use is viewed as a pressure exerted on the land surface. This pressure is then mediated to varying degrees by the production system but also the landscape attributes that characterise a farm. These attributes will determine the hydrological pathway water takes as it leaves the property and the likely attenuation that may occur. If a model lacks the structure to handle variation in landscape attributes or key datasets (e.g., soil) lack the most sensitive attributes relevant to contaminant loss, it is likely that considerable uncertainty will be present in model outputs (Bracken *et al*., 2013; Matott *et al*., 2009; Troy *et al*., 2008). One specific example of the importance of landscape context includes the role of preferential flow in response to shrink-swell clays or pedogenic structures (not mole-pipe drainage). Macropore bypass, especially bypass mediated by shrink-swell soils, is widely recognised as a key pathway of contaminant loss from farm (Clothier and Heiler, 1983; Beven and Germann, 2013; Kurtzman *et al*., 2016). However, if cracking soils are not represented by an existing soil survey or a model is unable to account for these sensitive landscape attributes, any estimated contaminant loss may be highly inaccurate. Currently, Overseer does not account for macropore bypass that relates to natural pedogenic factors.

To handle macropore bypass phenomena, two-domain soil models of solute transport have been developed, where the soil's water content is divided into either macropores (mobile water) or matrix (immobile water). A well-known example of this type of model is the MACRO model (Jarvis, 1994).

This discussion highlights concerns with the Overseer model:

- The hydrology sub-model introduces additional processes and mechanisms that are extremely difficult to parameterise;
- The complexity fails to address correctly the mechanisms that generate surface runoff;
- Field soils display far-reaching and preferential flow through macropores, and this is not addressed; and
- In its current form, the relevance of Overseer estimates of nutrient losses is limited to a narrow set of landscape attributes (see also 5.25.3).

8.2 NITROGEN AND PHOSPHORUS DYNAMICS

The focus of nutrient losses in the regulation of freshwater systems is on nitrogen and phosphorus, since these are the main sources of freshwater pollution. However, Overseer does not appear to account for surface losses of nitrogen and, therefore, may significantly underestimate total nitrogen loss from the farm. Phosphorus loss is risk-based and likely highly uncertain. To this extent, it appears that Overseer is primarily calibrated towards estimating nitrate leaching loss in soil drainage water. Critically, ecosystems respond to total nitrogen and total phosphorus losses from farm. As noted in 5.3 and 8.1.2 the form and abundance of nitrogen and phosphorus species lost from farm will vary according to the landscape setting. As such, a low nitrate loss may not equate to a low ammoniacal nitrogen, organic nitrogen or phosphorus loss.

8.2.1 Nitrogen dynamics

The primary inputs of nitrogen to the soil are dung, urine, plant litter and roots, and fertiliser (although there will be atmospheric depositions as well). Fertiliser inputs of nitrogen can be in the form of urea ($(NH_2)_2CO$), ammonium, nitrate, or organic matter. Organic matter breaks down and nitrogen can be

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[24] In other words, areas of hill country that are flat, such as the flat top of a hill.

mineralised or immobilised during this process, depending primarily on the nitrogen content of the organic matter and its efficiency of breakdown. The nitrogen cycle is illustrated in Figure 8.1.

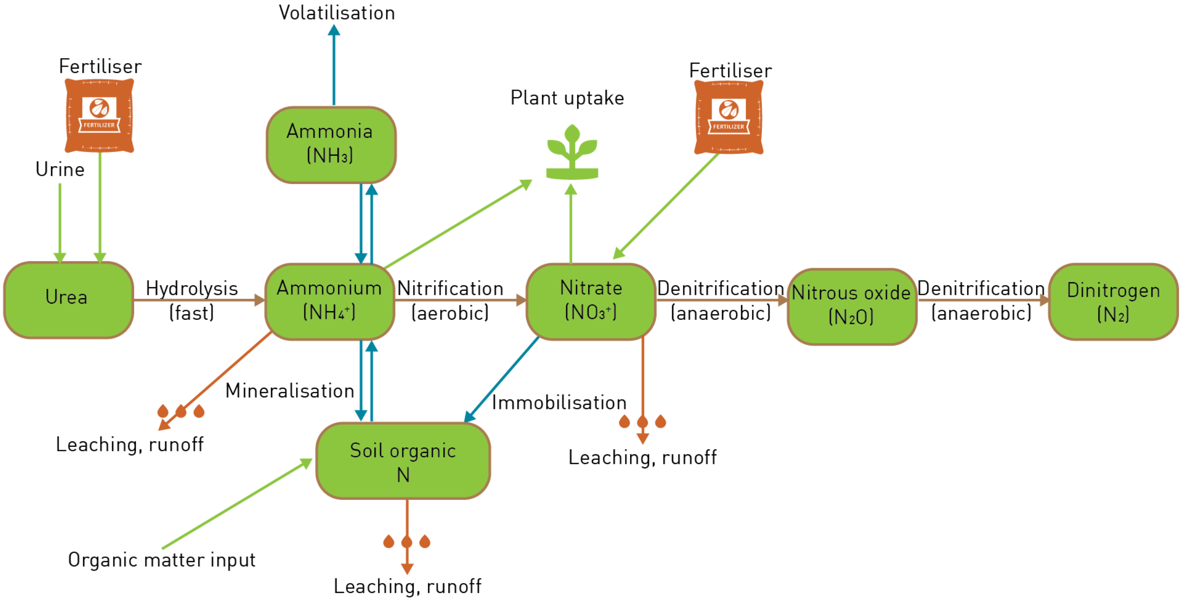

Figure 8.1 An illustration of the pathways for nitrogen transformation and losses

Regardless of the source of nitrogen, the principles in Figure 8.1 apply. However, Overseer appears to treat the various nitrogen inputs in different ways. Overseer has a separate, specific treatment of urine patches. The nitrogen cycle is modelled differently in the urine patch to the rest of the paddock. In this section we describe the nitrogen model outside of the urine patch. The urine patch model will be discussed in 8.3. There is no direct treatment of ammonia or ammoniacal nitrogen, although volatilisation losses (atmospheric emission of ammonia gas) are included for fertiliser (Wheeler and Watkins, 2018a) and urine depositions (Wheeler, 2018q). There is no treatment of organic matter dynamics and associated nitrogen dynamics, nor is there any treatment of surface losses of organic matter including dung, which generally have a significant nitrogen content. This is concerning given these forms of nitrogen may be exported from farm via leaching, artificial drainage and/or surface runoff.

The two forms of inorganic nitrogen in the soil are nitrate (NO_3^-) and ammonium (NH_4^+). These are both available for plant uptake, but there are important differences in their characteristics. Nitrate is subject to denitrification, which is the gaseous loss of nitrogen as both nitrogen gas (N_2) and nitrous oxide (N_2O). Volatilisation of ammonium results in the emission of ammonia gas (NH_3). Both processes respond to short-term daily climate and soil factors and can be highly episodic. Nitrate is highly mobile in soil due to its negligible adsorption characteristics, but ammonium is generally much less mobile because it tends to adsorb to the soil particles, particularly in soils with a high clay content. However, in sandy soils there can be significant movement of ammonium and potentially dissolved organic nitrogen. Furthermore, ammonium is the first inorganic form of nitrogen that is produced through organic matter turnover, so the distribution of ammonium in the soil profile is an important characteristic of nitrogen dynamics.

Outside of the urine patch, Overseer does not model the dynamics of *in* situ ammonium nitrification (the formation of nitrate from ammonium) through time. It does not model the dynamics of organic matter accumulation and turnover or the role of nitrate and ammonium in those processes. However, it appears that for ammonium inputs, there is an initial calculation for volatilisation and then it is assumed that all the nitrogen in the soil is nitrate – ammonium does not appear to be modelled directly (Wheeler and Watkins 2018a; Wheeler, 2018q). The urine patch sub-model does allow for nitrification over a period of up to three months. It is concerning that ammonium volatilisation is modelled in different ways in different parts of the model. In Wheeler and Watkins (2018a) volatilisation loss is calculated using average daily rainfall for the month, average monthly temperature, average monthly soil moisture down to 0.6m (relative to field capacity), a crop cover factor, soil sand content, and the amount and type of nitrogen fertiliser applied. This incorrectly ascribes some volatilisation losses to nitrate fertiliser applications. In urine patches, on the other hand, the proportion of nitrogen lost via volatilisation is only influenced by the average monthly temperature (Wheeler, 2018q; see 8.3). In some of Aotearoa New Zealand's landscapes, particularly imperfectly to poorly drained soils and areas with significant topographic relief (e.g. hill country), surface runoff of organic nitrogen and ammonium may be significant. As Overseer does not appear to be calibrated to consider surface nitrogen losses, models some processes associated with ammonium inconsistently, and does not account for organic nitrogen losses, this is concerning for Overseer's use as a regulatory tool.

Overseer also does not explicitly address organic matter dynamics. Soils generally contain a large amount of organic carbon. As a rule-of-thumb, the top 0.1m of soil is equivalent to a bit over 1,000 t ha^{-1} of soil. So, every 1% soil carbon content is approximately 10 t ha^{-1} of carbon and 1 t ha^{-1} of nitrogen. Changes in this soil organic matter pool can result in mineralisation or immobilisation of inorganic nitrogen (see Figure 8.1). Furthermore, dissolved organic forms of nitrogen may be labile and subject to transport by water. Soil organic matter dynamics are a central component of the overall system dynamics, so their omission is a weakness of the model. Soil organic matter dynamics are linked to nitrogen dynamics. Therefore, agricultural practices that lead to changes in soil organic matter will also lead to changes in nitrogen dynamics (see 7.3.8), but Overseer does not model these processes.

The use of a monthly timestep is also concerning. For example, in Overseer, leaching is related empirically to drainage and plant available soil water, based on monthly averages (Wheeler, 2018q). This would be simpler with a daily time-step and a multi-layer soil model that captures water and nutrient distribution through the soil profile. Movement of water through a layer in the soil profile only occurs when soil water content exceeds field capacity in that layer, so it is unclear why leaching is related to plant available water. Another example is denitrification. Denitrification varies both temporally in response to day-to-day climate and in all three spatial dimensions. Overseer's approach (Wheeler, 2018e) is based on Johnson *et al*. (2008), which is a biophysical pasture simulation model focusing on Aotearoa New Zealand grazing systems. It has a daily time-step throughout, while Overseer mixes daily and monthly time-steps. Furthermore, Overseer uses daily values for soil water status and average monthly temperature (Wheeler, 2018e), but the temperature response function is non-linear. Using an average monthly temperature is, therefore, unlikely to produce the correct monthly denitrification (as discussed in Appendix Two; also see Nonhebel, 1994). Furthermore, vertical and spatial variation in soil and topography plays a critical role in soil nitrogen dynamics. This variation affects the possible sub-surface lateral flow of nitrate, ammonium, and dissolved organic matter. Textural and topographic gradients drive spatial heterogeneity in the location that denitrification may occur.

8.2.2 Phosphorus dynamics

The documentation of phosphorus dynamics in Overseer is not complete (Wheeler, 2017), which makes it difficult for us to assess this aspect of the model. However, as far as we are aware, Overseer's phosphorus loss sub-model is based on McDowell *et al*. (2005) which estimates phosphorus losses due to runoff up to second order streams for a grazed pastoral system.

Both organic (e.g., inositol hexaphosphate) and inorganic forms of phosphorus ($[PO_4]^{3-}$) in soil are characterised by their high adsorption capacity, which tends to reduce its vertical movement in soil as a result of water infiltration and drainage (Walker and Syers, 1976; Crews *et al*., 1995). This means that phosphorus is not normally prone to leaching, although this may not be the case for soils characterised by low anion exchange capacity, such as organic soils, sandy soils and imperfectly to poorly drained soils. Perching of water within the soil over long periods results in the dissolution of the oxides and oxyhydroxides of iron and aluminium, which govern phosphorus retention. For these reasons, wetland or hydric soils are associated with higher phosphorus losses than well drained soils characterised by an abundance of oxides and oxyhydroxides. Particulate forms of phosphorus are prevalent in agricultural landscapes, occurring in a sediment (both organic and inorganic) bound form. The main pathway for particulate phosphorus loss occurs via surface runoff, although it may also be elevated in mole-pipe drainage. Other forms of phosphorus include neutrally or negatively charged nanometre-sized colloids that may be highly mobile in both soils and aquifers (Ryan and Gschwend, 1990; Wolthoorn *et al*., 2004; Krueger *et al*., 2007; Trostle *et al*., 2016).

Some aspects of phosphorus dynamics in Overseer are discussed by Gray *et al*. (2016). This is an entirely verbal description and gives little insight into the underlying mathematical structure of the model – but mathematical description is essential for a detailed assessment of the model structure. However, the discussion suggests that lack of data is the limitation for model development whereas the underlying concepts behind phosphorus dynamics in agricultural systems are well-established (Olsen and Watanabe, 1957; Kaila, 1960; McColl and Gibson, 1979; Parfitt, 1980; Taylor and Kilmer, 1980).

We, therefore, conclude that it is not possible, with the information available to us, to give a detailed assessment of how phosphorus dynamics are modelled in Overseer.

8.3 THE URINE PATCH MODEL

In grazed pastures, urine patches represent potential hot spots for nitrogen losses in Overseer. Urine deposition by grazing animals represents an internal transfer of nutrients within the animal-plant-soil system from pasture to soil rather than an input, although the contribution from imported supplementary feed can be viewed as an input. However, the localised concentration of total nitrogen within a patch can be very high (200-2000 kg N ha^{-1}, Selbie *et al*., 2015) and in excess of what the surrounding plants can utilise. This excess of nitrogen is then vulnerable to loss via leaching or gaseous emissions.

As for any source of nitrogen, ultimately the nitrogen in the urine patch will be either immobilised in the soil organic matter pool, emitted as a gas via volatilisation or denitrification, taken up by the plants, or leached from the system in inorganic or dissolved organic forms (van Kessel *et al*., 2009; Clough et al., 2017). The amount of nitrogen lost by these different mechanisms depends on the relative rates of the processes shown in Figure 8.1, which in turn are dependent on the soil conditions over time.

Overseer uses a standard nitrogen loading of 750 kg N ha^{-1} for urine patches (Wheeler, 2018q). This is within the range of dairy cattle of 200-2000 kg N ha^{-1} from Selbie *et al*. (2015). However, the high level of variability of nitrogen loadings in urine patches is a source of uncertainty. The urine patch nitrogen is initially assumed to be in the form of ammonium (Wheeler, 2018q). This is reasonable given that urea hydrolysis is a rapid process (Sherlock and Goh, 1985), although recent studies suggest the formation and/or persistence of dissolved organic forms may be more important than currently acknowledged (Clough et al., 2017). With a reasonable model of animal metabolism, the actual nitrogen concentration in urine could be calculated based on requirements, diet and an assumed urine patch area, although Overseer is not structured in this way.

For each month the deposited urine in each paddock is treated as a single patch with an area calculated based on the total amount of urine deposited in that month and the standard loading rate. Scaling factors are applied to account for different animal species (deer, sheep and male cattle have lower leaching risk), whether the paddock is hard-grazed, or if the immobilisation potential for the site has been adjusted (Wheeler, 2018q). This scaling assumes that a percentage increase in the total urine patch area is equivalent to the same percentage increase in urine patch nitrogen loading. This would be true if all processes scaled with nitrogen loading. However, this is not the case. There will be a limit to how much nitrogen uptake within a given area can occur in a month. This means that there is likely to be disproportionately more leaching of inorganic and organic nitrogen, as well as gaseous nitrogen losses at high nitrogen loadings. Therefore, it would be more accurate to apply the modifications to the nitrogen loading in the urine patch simulation rather than to scale the results from a standardised patch.

Figure 8.2 shows the steps Overseer uses to calculate the nitrate leached from a urine patch in a specified month. Overseer uses an ammonium pool and three nitrate pools for the urine patch simulations. However, these pools are not used outside the urine patch model. The monthly loop continues until all the added nitrogen has been lost or 24 months have passed. It should be noted that there is no connection between the urine patch and the rest of the simulation – they are separate entities (Wheeler, 2018q).

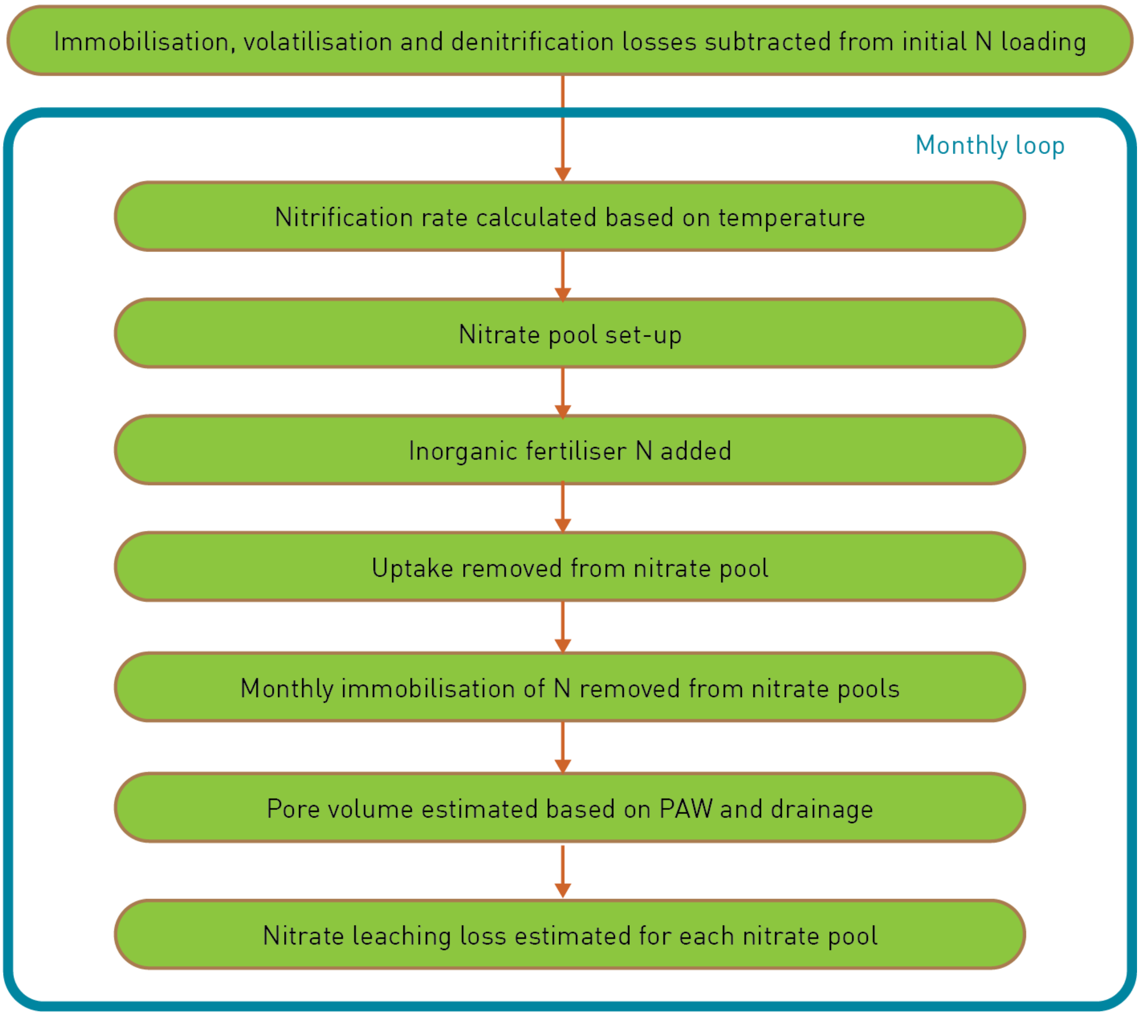

Figure 8.2 Procedure used by Overseer to calculate nitrate leaching from a urine patch (Wheeler, 2018q)

8.3.1 Initial immobilisation, volatilisation and denitrification losses

At the start of the urine patch simulation, Overseer removes nitrogen that is assumed to be lost through immobilisation, volatilisation and denitrification from the initial ammonium pool. For immobilisation, this represents only the initial nitrogen immobilised, but for volatilisation and denitrification this represents the total losses via these mechanisms (Wheeler, 2018q). This is reasonable for volatilisation which mostly occurs within the first two weeks following urine application and usually peaks within 1-2 days of urine application. However, denitrification occurs after nitrification (see Figure 8.1) and, so, if the nitrification rate is slow then the denitrification losses will also be delayed.

The initial immobilisation is a fixed proportion depending on what the nitrogen immobilisation potential has been set to (standard, high, or none). This represents net immobilisation caused by the flush of microbial activity following urine application. For standard nitrogen immobilisation, the proportion is 0.20 (Wheeler, 2018q). The subsequent remineralisation of the immobilised nitrogen is neglected on the assumption that it is a slow process that will not affect leaching (Shepherd and Selbie, 2020). This treatment of immobilisation is somewhat arbitrary and is likely to be unrealistic. Also, it is not clear whether this is net or gross immobilization although, given that organic dynamics are not considered, we assume this is net. Since immobilisation and mineralisation are part of the soil organic matter dynamics, it would be more appropriate to have a single consistent treatment of organic matter dynamics that considers specific soil conditions.

The proportion of nitrogen, as ammonia, lost via volatilisation is calculated using a formula based on the mean monthly temperature and can range from 0.10 to 0.20 (Wheeler, 2018q). The mean measured ammonia loss from urine patches on Aotearoa New Zealand grass patches has been reported as 15.9% (Sherlock *et al*., 2008). However, the variability is high with a coefficient of variation of 96%. Factors influencing ammonia volatilisation include pH (which may be locally increased by urea hydrolysis), soil temperature, wind speed, soil moisture, and evapotranspiration; it is also suppressed by rainfall (Selbie *et al*., 2015). Volatilisation losses are rapid with emissions usually peaking within 1-2 days of urine application (Whitehead *et al*., 1989). This means that it is reasonable to subtract these losses from the initial nitrogen pool. However, it also means that the weather conditions at the time of application are more relevant than the monthly average.

In contrast to the treatment of volatilisation from urine patches, for fertiliser applications a different volatilisation formula is used that has the average daily rainfall for the month, average monthly temperature, average monthly soil moisture down to 0.6m (relative to field capacity), a crop cover factor, soil sand content, and the amount and type of nitrogen fertiliser applied. However, the fertiliser formula incorrectly ascribes some volatilisation losses to nitrate fertiliser applications (Wheeler and Watkins, 2018).

Denitrification, on the other, hand occurs after nitrification in the reaction sequence. A single denitrification emission factor (adjusted if there is pugging) is used to calculate total denitrification losses. The documentation for the denitrification calculation is not very clear and many of the equations do not clearly state the units of all the terms making them difficult to interpret. However, our understanding is that emission factors are calculated based on the soil type, water filled pore space and temperature for each day of the month and then averaged (Wheeler, 2018q). This seems to be mixing the concept of an emission factor that gives the expected total losses, with a daily time-step model. In addition, most of the parameterisation appears to have been geared towards fitting nitrous oxide emissions rather than denitrification rates. Overall, it seems inconsistent to have nitrification calculated on a monthly time-step, but an emission factor approach used for nitrous oxide. Also, since pugging is likely to be associated with high rainfall, it may not be accurately captured using average climate.

8.3.2 Nitrification

The monthly nitrification rate is calculated from a daily nitrification rate based on the mean monthly temperature (Wheeler, 2018q). The nitrification rate has no moisture dependence, which is commonly included in nitrification models (e.g., Li *et al*., 1992, Parton *et al*., 1996).

8.3.3 Nitrate pool set-up

The nitrate produced by Overseer each month is treated as a unique pool. This is because Overseer doesn't track the location of the nitrate within the soil profile and instead uses breakthrough curves (see below) that must be calculated separately for nitrate produced in different months (Wheeler, 2018q). However, given that nitrification is a continuous process, it would be more realistic to calculate nitrification daily and to simulate its transport through the profile.

Nitrification is assumed to be completed by the third month with all remaining ammonium being added to the nitrate pool (Wheeler, 2018q). This seems to be arbitrary and denies the possibility of variation in climatic factors influencing the timeframe of the process.

8.3.4 Uptake removed from nitrate pool

The monthly plant nitrogen uptake is calculated based on a base rate (for pasture) modified by regional and climate factors. There does not seem to be any check that the total pasture nitrogen uptake rate from the urine patch is consistent with the amount used in other parts of the model. The plant nitrogen requirement is removed first from the nitrate pools, and then only from the ammonium pool if there is insufficient nitrate (Wheeler, 2018q). However, pasture species can take up both ammonium and nitrate (e.g., Høgh-Jensen *et al*., 1997) so arbitrarily preferring nitrate for uptake could bias leaching estimates.

8.3.5 Monthly immobilisation removed from nitrate pool

The term immobilisation refers to the incorporation of nitrogen into soil organic matter by microbial processes (see Figure 8.1). However, Overseer does not represent soil organic matter dynamics, so the nitrogen is not actually immobilised. Instead, the numerical amount of nitrogen is reduced in the model as an approximate adjustment of the nitrogen that would be immobilised in the real world. As mentioned above, imposing an immobilisation rate on the nitrate may not be generally applicable. Notwithstanding this point, the fraction of the nitrate pool immobilised into the soil organic matter each month is calculated using a monthly immobilisation rate (0.025 for standard soils) modified by the same temperature factor used for organic matter decomposition (Wheeler, 2018q). Again, the assumption that immobilisation is assumed only to apply to the nitrate pool seems hard to justify. According to Rochester *et al*. (1992) nitrate is only immobilised in preference to ammonium in neutral to alkaline soils, while ammonium is preferentially immobilised in acid soils.

8.3.6 Leaching nitrogen loss calculated for each nitrate pool

Overseer makes no attempt to model nitrogen dynamics, including leaching, explicitly in urine patches in response to climate inputs. Instead, an empirical model was fitted to the results of some previously calculated nitrate leaching values using APSIM. The fitted model used:

- Annual rainfall;
- Rainfall for six months from the time of urine deposition;
- Average temperature for six months following urine deposition;
- The fraction of the profile available water that has water present;
- Soil water content for the month of urine deposition;
- Soil water content at wilting point; and
- Profile available water at 0.6 and 0.75m.

to predict the proportion of the total nitrate leaching that occurred at a given level of drainage (in units of pore volumes). These curves are referred to as 'breakthrough' curves (Cichota *et* al., 2012; Wheeler, 2018q). However, with so many layers of abstraction/simplification (an empirical model of a process-based model, use of average climate data, ignoring the vertical distribution of the nitrogen in the soil) this approach is so far removed from what is happening in the paddock in relation to current daily climate patterns that it seems to have little credibility – as we discussed in Chapter 4, any assessment of the model must consider not only isolated model simulations but also the credibility of the relationship between inputs and representation of system behaviour.

It can only be assumed that this approach is an attempt to address the computational complexity associated with modelling many urine patches. While modelling individual patches is certainly computationally demanding, there is an obvious potential to incorporate mathematical methods to model categories of urine patches rather than explicit patches. This will ensure that the overall vertical and lateral heterogeneity in nitrogen distribution in the soil is accounted for through time, while not modelling urine patches in isolation. This would also have the clear advantage of not separating the urine patches from the rest of the simulation.

Nitrate is the only form of nitrogen that is assumed to leach in Overseer.[25] While nitrate tends to be the major form in which nitrogen leaches from the soil, some studies have found dissolved organic nitrogen (DON) in leaching water (van Kessel *et al*., 2009). Organic forms of nitrogen leaving via ditch, mole-pipe, nor surface runoff are not considered. This relegates Overseer to estimating but one of the key nitrogen species relevant to water quality.

8.4 FINDINGS

In our view, Overseer's treatment of hydrology and nitrogen dynamics is flawed. We are unable to give an adequate assessment of phosphorus dynamics due to the lack of documentation. Ammoniacal and organic forms of nitrogen losses are not considered, relegating Overseer to estimating but one of the nitrogen species relevant to water quality: nitrate. Given the importance of nutrient distribution through the soil profile to leaching and the prevalence of multiple layer models, a single layer hydrology model seems inadequate. Overseer models soil water balance in the top 0.1m, 0.6m, and 1.5m of soil but not how they are related. Overseer does not consider natural bypass through the soil (i.e. cracking soils) or the preferential flow of water and nutrient through the soil profile. Similarly, Overseer does not explicitly consider soil organic matter dynamics and their effect on nitrogen dynamics. There is also no specific treatment of dung dynamics or their contribution to surface losses of nutrients through runoff. Nitrogen dynamics are treated inconsistently throughout the model, in particular, denitrification and volatilisation. Furthermore, this is concerning for kaitiaki who view Papatūānuku holistically at the very least, as there is no consistent picture of the whole system.

The model calculates daily drainage (using average climate) and then aggregates this to monthly values for leaching calculations. This precludes the treatment of pulses of water or nitrogen through the soil profile in response to short-term periods of high rainfall. Also, since the model uses the ratio of

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[25] As far as we could determine, phosphorus leaching is not included in the model.

drainage to average soil water content to define leaching, this ratio can exceed 1; the model has adjustments for this situation, but it is physically unsound.

Overseer assumes that the plant nitrogen uptake and immobilisation will primarily affect the nitrate pools. This is a potential source of bias in leaching estimates as the nitrate pools are the only ones susceptible to leaching in Overseer. There are also concerns about the timescales and use of breakthrough curves in the urine patch model. Also, urine patches are not integrated with the bulk soil and edge effects are not considered. It is also concerning that nitrogen immobilisation potential is chosen by the user. Overall, the hydrology and nutrient models have unnecessary simplifications, omissions, and inconsistencies that raise serious doubts about their applicability for predicting nutrient balance in agricultural systems.

Finally, as Overseer only appears to estimate nitrogen losses from below the root zone, a potentially large contribution of nitrogen in runoff is ignored. It is estimated that runoff via overland flow is an important hydrological pathway for nitrogen loss across over 80% of Aotearoa New Zealand’s productive land. Critically, across this large area a low nitrate loss estimate may not equate to low ammoniacal nitrogen, organic nitrogen, or phosphorus losses from farm. Overseer could include an estimate of nitrogen loss via runoff by considering the role of landscape attributes such as topography and soil hydrology over hydrological pathways and other important biogeochemical processes.

9 Assessment of Overseer’s model structure

In Chapter 6 we found that, based on the animal metabolism models, Overseer should be used with caution as a decision support tool and in regulation. In Chapter 7 we came to the same findings regarding the modelling of pasture, crops and horticulture. In Chapter 8 we found many limitations in hydrology and nitrogen modelling, and insufficient information to assess phosphorus modelling. We will now look at the overall structure. Issues with individual components may be able to be solved relatively easily, but if the structure is inadequate this is a major problem.

9.1 CORE MODEL STRUCTURE

There are three basic model structural characteristics that are out of step with good practice and modern model design. Overseer:

- uses a form of average climate data;
- does not calculate plant growth in response to climate, soil water, or nutrient status; and
- does not necessarily balance mass.

We shall look at these points in turn to explain whether they impact on Overseer’s outputs to such an extent that they affect whether the model is fit-for-purpose for use in regulation and/or as a decision support tool.

There are other important model structural factors discussed in earlier chapters but not repeated in this section:

- The model uses single unrelated soil layers rather than allowing for the distribution of soil water, nutrients, and plant roots through the soil profile (see 8.1.1)
- Overseer does not include an explicit treatment of ammoniacal and organic nitrogen (see 8.2.1)
- The model takes no direct account of the dynamics of soil organic matter changes through time (see 8.2.1)
- The treatment of nutrient leaching is not consistent for the overall soil profile and urine patches in pastures (see 8.3).

9.2 AVERAGE CLIMATE

Climate data drive core processes in any agricultural system. However, rather than use actual daily climate data, Overseer uses averaged climate data. Furthermore, while this approach may have been reasonable during Overseer’s development, daily climate data are now readily available (see Chapter 5), and have been for several years (e.g., Cullen *et al*., 2008). Techniques to produce synthetic climate data using weather generators have also been available for around 40 years, if not longer. These were discussed briefly in 5.1.

Appropriate timescales for climate and management inputs are fundamental to the model. In Overseer, management represents average management over the year. In practice, management varies in relation to prevailing circumstances, including climate, so management inputs should reflect prevailing climate. As discussed in 5.2, Overseer users’ options are to average their management data or use their actual annual management data (assuming these are representative of the long-term average) as inputs to the model. There are advantages and disadvantages to each approach. Determining how to average management data is difficult but combining annual management data with average climate data can lead to inconsistencies. The use of average climate, therefore, constrains the model’s ability to reflect how management varies through time in response to prevailing conditions.

We can see no reason not to use the readily available daily climate data that, with a sound model, provides information on variation in system behaviour far beyond looking solely at averages. In Appendix Two, we looked at some basic simulation analysis for a representative site in the Canterbury Plains region. The use of actual daily climate data is more appropriate than using some form of averaged data with a mixture of daily (rainfall) and monthly values. We saw that the use of average climate is not justified. In more general terms, based on basic mathematical principles of non-linear systems and a brief analysis of some appropriate climate data, there is no rationale for applying average climate data (Nonhebel, 1994). It is difficult to predict how average climate data affects the reliability of Overseer’s nutrient loss estimates; therefore, it is difficult to have confidence in the results.

It would be more appropriate to use the readily available actual climate data and then extract appropriate statistical information from the simulation results. As well as using average climate data, Overseer also requires average monthly management inputs, which further limits its ability to respond to interactions between actual climate and management. Furthermore, the use of average climate data limits the ability of kaitiaki to respond to impacts on Papatūānuku as it makes looking into the future more difficult, particularly to understand the potential effects of climate change.

Wheeler *et al.* (2018, p. 22) say "Limited unpublished data indicates that using annual management data and long term climate data, and averaging the outputs over time provides a reasonable indication of the nutrient budget when average management data is used*".* Ideally, simulations would be run to test these underlying model assumptions. Overseer has in the past been compared with IrriCalc[26], which uses daily climate data, and results were similar (Wheeler and Bright, 2014). Simulations were run with IrriCalc to analyse long-term soil water balances, the results of which were then used to derive average soil water balance, in particular drainage. The results were compared with Overseer and gave quite good agreement for annual values for drainage. This was regarded as an excellent result. However, runoff was not reported, so we assume it was not a significant component of the simulation. Since the IrriCalc simulations were run over 30 years, it is reasonable to assume that the overall change in average soil water content was quite small; for Overseer, there is an assumption of steady state so we can also assume that the change in soil water content for the average year was also quite small. This means that the analysis is comparing annual drainage and annual evapotranspiration. Since potential evapotranspiration (at least in the case of Overseer) is an input, it is not surprising that the two models have similar evapotranspiration values. This then leaves drainage and, given the fact that water can only go either up (evapotranspiration) or down (drainage) it is not surprising that the two models gave similar agreement. We therefore find this comparison to be a weak test of the model.

Overseer's use of average climate data is a fundamental weakness. Furthermore, based on the discussion earlier about testing and evaluating models (see 4.2), this analysis comparing Overseer with IrriCalc is very limited. To the best of our understanding, there have been no real attempts to assess the accuracy of using average climate to simulate long-term system behaviour. This should be relatively straightforward; the analysis inAppendix Two: Climate and time-steps Appendix Two that looks at this problem with a different model is quite simple.

9.3 MODEL TIME-STEP

Overseer uses a mix of daily and monthly time-steps. As mentioned above, a form of average daily rainfall is generated and used in the hydrology component, while other climate factors are represented by monthly averages. Once the hydrology component has been run, the results are then aggregated to monthly and other model components are run with this monthly time-step. There seems to be no sound rationale for this approach.

It may seem that moving the whole model to a daily time-step would require more user input data. This need not be the case. For example, moving stock on and off a paddock is represented by two points in time which must be defined regardless of the model's time-step. Any well-constructed model should be able to accommodate these types of specified inputs.

9.4 SPECIFICATION OF PLANT GROWTH

Overseer does not calculate plant growth in relation to climate conditions. Rather, for pastures (see 7.2) it is back calculated from user-inputted animal production and supplementary feed values, while for crops (see 7.3) it is back calculated from a specified crop yield. Variable plant growth will likely cause variability in nitrate leaching because plants take up nitrate and water. High growth gives high uptake and lower leaching, with low growth giving the reverse. Ignoring this variability has several implications. Firstly, if the specified plant production is over- or under-estimated, leaching will be under- or over-estimated. Secondly, as demonstrated in Appendix Two, the non-linearities in the processes linking plant growth to leaching mean that leaching estimated assuming constant conditions (plant production and climate) will not equal what would have occurred if the temporal dynamics of those two factors were explicitly taken into account. This is concerning for Overseer's ability to provide kaitiaki with an understanding of taha tinana of Papatūānuku.

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[26] Note that IrriCalc is a single-layer soil model. We have discussed the limitations in this approach for describing nutrient dynamics in soils.

9.5 MASS BALANCE

Overseer does not balance mass. It balances the movement of nutrients between blocks, but there is no guarantee that mass balance is preserved for actual nutrient dynamics in crops and pastures. Over the duration of the model run, the amount of nitrogen initially in the system plus the amount added may not equal the amount at the end of the run and the amount removed. This problem is evidenced by the existence of the terms “balancing error” in the pasture model (7.2.4) and “nitrogen deficit” in the crop nitrogen model (7.3.3). These terms correct the numerical inequality but don’t restore mass balance in the formal sense of the process. Mass balance is a core requirement of any model that aims at reliably tracking water and nutrient dynamics. If mass is not balanced, the user cannot have confidence in the model outputs as the user cannot know if any nitrogen was lost from the system and if so, how much. As above, this limits Overseer’s ability to help kaitiaki understand the taha tinana of Papatūānuku.

9.6 FINDINGS

Based on the structural characteristics addressed here and earlier in the report, Overseer’s structure does not give us confidence that it can be used for the purposes discussed in Chapter 2; to provide us with estimates, that we can have confidence in, of the direction and magnitude (and associated error) of the change in nutrient losses from a farm due to management changes. This is discussed further in Part 3: Conclusions below.

Part 3: Conclusions

10 Implications

10.1 INTRODUCTION

In Chapters 6-9 we described different aspects of Overseer's modelling approach, including strengths and challenges associated with the model's components focused on climate, animal production and metabolism, pastures, crops and horticulture, and soil water and nutrient dynamics. We now bring together these discussions into an overall assessment of the implications of using Overseer, in its present form, for regulatory and decision support functions.

10.2 OVERSEER'S ADEQUACY

In Chapter 4 we set out some key evaluation criteria for assessing model adequacy. These are:

1. Model structure: does the model structure suit the objectives of the intended model application?
2. Data used in model development: are the data used to inform the model structure appropriate and adequate?
3. Model behaviour: does the model provide sensible and robust outputs?
4. Model sensitivity: how sensitive is the model to variation in input parameters and driving variables, such as climate, and is the sensitivity realistic?
5. Agreement with experimental data: does the model give good agreement with appropriate available experimental data?

We will now use these evaluation criteria to assess Overseer's adequacy and to discuss the resulting implications for Overseer's use in policy and decision support.

10.2.1 Model structure

Overseer's structure is not traditional in the context of both agricultural systems and ecosystem models. Ecosystem models generally have climate as a primary driver of the ecosystem response, given the soils, plant communities, etc, present in the region being analysed. For agro-ecosystem models, management is also an important driver; e.g., what crops or pastures are grown, how much fertiliser is applied, are they irrigated?

A simplified flow diagram of an agro-ecosystem model is shown in Figure 10.1. Climate, farm management (that includes specification of pasture or crop type, animal production, etc) and soil information need to be specified, and growth processes and flows of water and nitrogen are emergent properties of these drivers. In Overseer however, animal and plant production and farm management are user inputs (Figure 10.2). Neither the production inputs nor management is directly affected by climate. In Overseer, climate, soil properties, and the emergent processes and flows determine the amount of nitrogen leached from the farm in response to management practice, including fertiliser application and irrigation.

While the calculation of the emergent processes and flows in Overseer, and the equations and parameters on which they are based, is very complex, the structure of the model, in particular the use of average climate and the lack of any quantitative assessment of variation in nutrient losses in relation to climate, means that the single constant output value derived by Overseer is compromised by not using actual climate data inputs. The biophysical complexity that results in year-to-year variability is not accommodated in the model structure. Pastures or crops grow more or less in one year than another. Nitrogen is emitted to the atmosphere (by the processes of volatilisation and/or denitrification) more or less in one year than another. These and other processes result in leaching and surface losses of nutrients being more or less in one year than another.

A model can still provide a long-term estimate of nitrogen leaching and surface flows by modelling a series of individual years, thus capturing variability more accurately, and then averaging all those years afterwards. In fact, modelling individual years (or shorter time periods) and averaging these outputs represents the long-term average accurately, whereas averaging inputs (e.g., rainfall) does not produce a long-term average accurately (see Appendix Two). By understanding the variation in these processes as well as the average, it is possible to identify conditions under which nutrient losses may be high and explore strategies that may help reduce these losses. This means that realistic long-term analyses provide more information of a greater accuracy than average-input analysis.

This raises the fundamental question as to whether the results that Overseer gets by using long-term average climate data are like those that would be obtained with actual climate data. There is enough evidence from our basic analysis in Appendix Two to suggest that the results would be different. Even if the aim is to look at averages only, and to ignore all the useful information that can be gleaned from variation about the average, we are certain that the use of average climate data cannot be guaranteed to give similar results to those obtained from using actual climate data and averaging the results (Nonhebel, 1994).

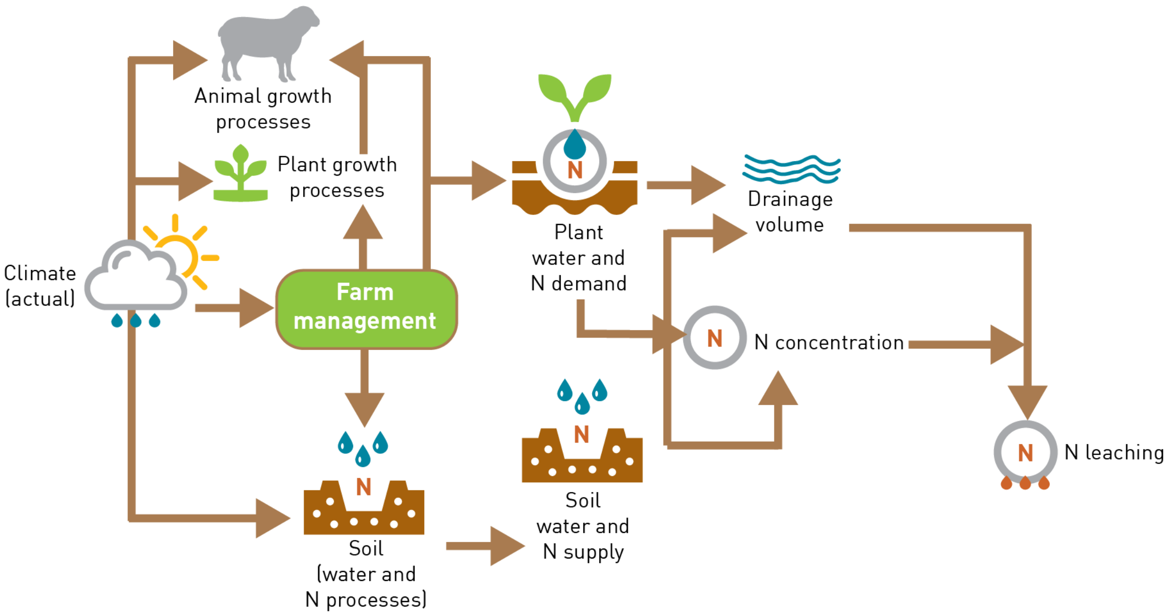

Figure 10.1 Simplified representation of a typical agro-ecosystem model, where the arrows indicate the influencing factors. Inputs are shown in bold and the emergent properties in italics. NB: the link between animals and soil nitrogen is omitted for simplicity.

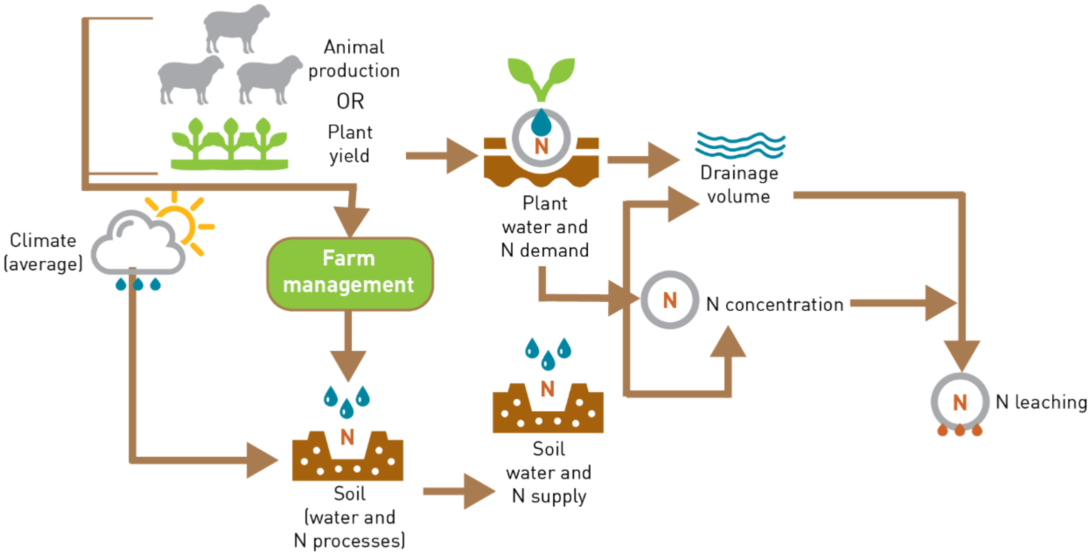

Figure 10.2 Simplified representation of the Overseer model, where the arrows indicate the influencing factors (as described in Figure 9.1). The link between animals and soil nitrogen is again omitted for simplicity.

Based on the documentation and discussion with the development team, Overseer's structure was arrived at partially because of the availability of data, the usability of the tool, the assurance that users would input realistic scenarios, and the history of model development. Overseer predicts inputs from outputs, which is a benefit to the usability of the tool because it uses information currently available to farmers. Overseer relies on users to self-check that scenarios are realistic, which is a benefit because it alleviates the need for the model to predict sensitive output variables that users already know (e.g., production level). Finally, the tool can use datasets automatically (e.g., climate data), which improves usability and reduces the burden on the user to source data that may not otherwise be available (e.g., soil characteristics).

Over time, Overseer has migrated from its original intended application to be used for a variety of regulatory decisions. This is problematic because in some of these cases, the strengths of Overseer (efficient use of available data, usability of the tool, reliance on user knowledge) become limitations. To illustrate the implications of these vulnerabilities, we evaluate the Overseer structure based on three questions:

- Is the structure of the model (inputs, relationships, outputs) sufficient to describe the biological, chemical, or physical relationships needed to accomplish the end use?
- Does the structure of the model self-protect against out-of-range predictions?
- What type of output uses (prediction, scenario comparison, optimisation, etc.) are supported by the model structure?

Overseer's structure aims to explain biological, chemical, and physical relationships quantitatively, but it does not rely on first principles when attempting to explain these relationships. The structure does not describe actual biological, chemical, or physical relationships because it uses a biological system's outputs (e.g., milk, meat, wool) to calculate the system's inputs (pasture) (see 6.1 and 7.2.1). While this is advantageous in using readily accessible and meaningful input data, it limits the model's ability to predict nutrient losses under management practices for which historical production data are not available. The model does not conserve mass (see 9.5), an important first principle in modelling biophysical (and other) systems.

These two issues (failure to simulate underlying biological, chemical, and physical relationships; and failure to enforce conservation of mass) can lead to inaccurate representations of system dynamics. This means that the model can be set up to produce unrealistic results. Overseer has traditionally relied on users to input actual scenarios, because the input data were based on measurements and records for the farm. The model structure, therefore, supports a limited output use: prediction of nutrient loss based on past measurements and records. It cannot compare scenarios or optimise a farm system.

However, the model is sometimes used to predict nutrient losses based on target rather than actual production levels, for example for a resource consent application. Overseer Ltd advise that rural professionals estimate production for these future scenarios based on their expertise and that there is an extensive user support network established around the model, addressing this particular limitation. We consider that the model could be strengthened so as not to be reliant on expert users to address model limitations.

10.2.2 Data used in model development

Some of Overseer's sub-models and equations are empirical, meaning equations are fitted to data. Many of its parameters are also informed by experimental studies. It is, therefore, best suited to handle simulations that are within the data range used for parameterisation. In many cases, the data used in Overseer may not perfectly represent Aotearoa New Zealand's agricultural systems, but represent the best available data (e.g., energy requirements; see 6.2). However, in other cases, there are issues with the sourcing and breadth of data. One example is imported feed supplements. In Overseer, users can choose a feed supplement and use default values or enter their own. The default values of dry matter content, nutrient content, ME content, and digestibility are in Wheeler and Watkins (2018b, Table 10). "*These were derived from typical (not necessarily average) values of feeds measured by a commercial feed testing company (FeedTech*)." (Wheeler and Watkins, 2018b, p. 15). From this description, the details on how sampling was carried out or how much variation there was among samples is lacking. Collectively, evaluation of the data used to develop Overseer suggests several limitations. Some critical datasets are not good representations of Aotearoa New Zealand agriculture, which may lead to biased or erroneous prediction dynamics. Other critical datasets are not well documented, which makes evaluating them difficult.

As discussed in 10.2.1, the Overseer software team has worked to automate entry of challenging data, such as soil and climate information. Unfortunately, the model structure has not been updated over time to keep up with modern data. For example, the model was originally structured around average climate data because those were the data available. However, as datasets based on daily climate observations have become commonplace,[27] the model structure was not updated to use this new resource. As such, the model suffers from generalising predictions that, by mathematical certainty, are not representative of predictions that would be attained from actual climate data (see Appendix Two and Nonhebel, 1994). The consequence of the outdated data sourcing within Overseer is that the model will fail to account for the variation in outputs associated with true climate and may over- or under-predict nutrient outputs as a result. Because the exact magnitude and direction of the misestimation will vary by year, this shortfall impedes the ability of the model to predict absolute values or relative differences. Although it may be tempting to suggest that average climate data and average output data may be similar, it is clear from the analysis in Appendix Two and the literature (e.g. Nonhebel, 1994) that this cannot be guaranteed.

In many cases, Overseer was built on and uses the best-available data. However, in some instances there are poor descriptions of data sources in the model's documentation, models derived from data not representative of Aotearoa New Zealand conditions, and outdated data used for equation development of model inputs. These limitations in data quality, coherence, and consistency impede the reliability of absolute and relative model predictions.

10.2.3 Model behaviour

Assessing model behaviour is closely related to assessing model structure. To assess model behaviour, we evaluated both the microstructural relationships and the effects of the macrostructure (discussed in 10.2.1) on model behaviour. In this case, we define microstructure relationships as individual behavioural responses within specific modules of the model (i.e. individual equations). Macrostructural relationships encompass the overarching model structure (e.g., time-step, inputs, outputs, etc.).

Numerous aspects of the model microstructure produce behaviours that are expected representations of known biological responses. For example, the relationships governing animal nitrogen excretion predominantly produce model behaviours that would be expected (see 6.2). However, there are several missing relationships within the model. For example, the model fails to account for how diet and physiological stage influence nutrient use efficiency of livestock (see 6.2). Additionally, neglecting the role of ammoniacal nitrogen, surface losses of dung, and organic matter dynamics (other than a basic assumption that there is an immobilisation of nitrogen in the urine patch model), with its associated net soil carbon increase, means that nitrogen losses may be systematically over- or under-estimated where the farming system practiced results in increasing or decreasing soil organic matter. Likewise, this assumption overlooks, and therefore cannot represent, the role that plant growth, fertiliser management and, increasingly in the future, climate has on soil organic matter levels (see 7.3). In addition to these missing relationships, there are some behaviours that are represented differently in different parts of the model. For example, the urine patch model (see 8.3) treats volatilisation and denitrification differently from how they are modelled elsewhere (see 8.2).

Often, when model behaviour is evaluated, we focus predominantly on these microstructural aspects of the model. In the case of Overseer, the concerns with the model macrostructure (time-step, quasi-equilibrium, climate data, conservation of mass, and prediction of inputs from outputs) suggest evaluation of macroscale behaviours is more important. The limitations of the overarching structure of Overseer notably impair the ability of the model to produce trustworthy absolute or relative predictions (see 10.2.1). These challenges with the overarching model structure are likely to overshadow any appropriately modelled behaviours represented by the model microstructure.

10.2.4 Model sensitivity

Assessing model sensitivity has many uses. It can help modellers confirm adequacy of relationships within a model or identify areas for future work. It can be used to inform end-use evaluation of model behaviours, or to aid in expert assessments of model performance. The pieces made available to the review panel showed promising sensitivity indices that reinforced known challenges within the model (e.g., pasture production is highly sensitive to pasture ME content) (Overseer Ltd, 2020b). As such, this analysis, when complete, will likely be a useful tool for Overseer Ltd to identify priorities for model improvements. Unfortunately, the indices presented to the review panel are largely simplistic. Until a more comprehensive global analysis is completed the results have minimal practical use for evaluating model performance. The implications of not having a good comprehension of model sensitivity is that we cannot confirm the model behaves as expected across a wide range of scenarios, we cannot

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[27] For example, data from the NIWA VCSN have been available for over 10 years.

confirm that the main drivers of model behaviour match expected biological drivers, and therefore we cannot provide commentary on how the sensitivity of the model affects usability.

10.2.5 Comparison with experimental data

Agreement between model observations and experimental data is a cornerstone of literature-based assessments of models. However, this is only one facet of model evaluation. With a large-scale model of natural phenomena, it is virtually impossible for there to be precise consistency between model inputs and the conditions under which the experimental data were collected (Oreskes *et al*., 1994). For example, an experiment to examine crop yield in response to phosphorus may show a response to sulphur if the fertiliser were applied as superphosphate. Another example is the comparison of soil water content between observation and measurement. Even if there is close agreement, the model could overpredict runoff and underpredict through drainage.

Much analysis and assessment of Overseer has focused on comparison with experimental data, often showing relatively unbiased and accurate predictions of the available observational data (e.g., Cichota *et al*., 2010; Shepherd, 2019; Wheeler *et al*., 2020a, 2020b). There are potential problems with these types of analysis. First, it is often not clear whether averages of actual climate data were used. If the inputs in the model and experiment are inconsistent, then the comparison is flawed. Second, comparisons with experimental data should provide an indication of error estimates in the experimental data. Another concern with comparisons between modelled and measured data is Overseer's focus on nitrate. Nitrate is likely to be the main source of nitrogen for limited landscape characteristics, so the explicit inclusion of other sources of nitrogen may be an important consideration. Similarly, if data come from an experiment where soil organic matter is changing through time, any agreement would be coincidental and not any reflection of the Overseer model. In other words, agreement with data is encouraging, but does not imply model 'truth'. Furthermore, if this agreement is reached with conflicting climate inputs, then the comparison is largely irrelevant.

The challenges of using relatively short-term experimental data to assess long-term average system behaviour is not lost on the Overseer team (Watkins and Shepherd, 2014; Shepherd and Wheeler, 2016; Wheeler *et al*., 2018). These authors point out that "Field trials used in the calibration of the N model have been typically conducted over 2 to 5 years duration (Watkins and Shepherd, 2014). The short duration of field trials provides challenges because these data cannot be considered 'long-term' and the run of years is unlikely to adhere to the long-term monthly climate inputs or distribution patterns used within Overseer" (Wheeler *et al*., 2018, p. 15). Wheeler *et al.* (2018) also discuss how Overseer is manipulated so estimated annual drainage is similar to experimental measurements; "Overseer inputs were entered, based on the best available information, and then adjusted so that the estimated annual drainage was the same as values reported in the experiments. Default (long-term) climate patterns were used because there were embedded in Overseer" (Wheeler *et al*., 2018, p. 15). This means the model is being compared with experimental data where the climate inputs to the model are not consistent with those that occurred during the period of the experiment. This reduces the confidence we can have that simulation conditions and inputs are as close as possible to the conditions under which experimental data were collected. Furthermore, drainage should be viewed as a model output, not something than can be used to adjust model inputs.

Overseer has also been tested against outputs from more complex agricultural systems models (e.g., Wheeler and Bright, 2014; Vibart *et al*., 2015; Khaembah and Brown, 2016). These studies assume that the greater complexity of these models results in their outputs being closer to "reality". Some of these reviews suggest that certain model components have promise. However, these studies do not substitute any of the other requirements for model evaluation discussed here.

All models are simplifications. However, in building a model it is important to identify those factors that are most relevant to the aims of model application. This raises the question of how reliable a model may be, even if it shows some agreement with experimental data, if key model components are absent. The omission of dynamic treatment of ammoniacal nitrogen, surface dung losses, and landscape characteristics are causes for concern. The implications of these missing components cannot be assessed by comparisons with experimental data.

Comparing a large agroecosystem model to measured observational or experimental data is a tremendous challenge, one not commonly attempted in literature. A key limitation is that it is difficult to obtain error estimates for the observational data. It is, therefore, not surprising that a comprehensive and systematic evaluation of Overseer's predictions has not been conducted. Indeed, the limitations of the model's structure effectively prohibit the usefulness of such an exercise. It is therefore important that the underlying model structure is sound, as it would be unsound to base model evaluation solely on the limited data available.

We introduced the concepts of accuracy and precision in Chapter 4. Both accuracy and precision play and important role in influencing model adequacy; models must be accurate and precise enough for the purpose for which they are used. Given Overseer's use, we need confidence that Overseer's modelled outputs provide us with estimates of the direction and magnitude (and associated error) of change in nutrient losses from a farm due to a change in farm management. We are concerned that it is not sufficiently accurate or precise for this purpose. As explained in section 4.2.5.1, using a model to conduct relative predictions does not excuse the need for the model to be accurate and precise.

10.3 EPISODIC WEATHER EVENTS

Overseer is not designed to provide strategies to response to weather events that differ from the average. This is a limitation. For example, runoff is generally associated with high, short-term rainfall events. These events are likely to result in runoff, particularly on sloping paddocks. This may, in turn, result in substantial surface losses of soil organic matter and nutrients. Similarly, extended dry periods may lead to cracking soils. When it then rains there may be significant water, and possibly nutrient, movement through these cracks and into the deeper soil profile. This may, in turn, lead to nutrient leaching not accounted for by considering soil water infiltration alone.

Farmers should not be penalised for extreme weather events, such as catastrophic floods or storms. These catastrophic events also present different modelling challenges. However, episodic events, such as short-term heavy rainfall, are common. Their omission is a crucial limitation to Overseer and its application. This is a fundamental weakness of the use of Overseer for quantifying nutrient leaching and modelling the overall water and nutrient dynamics, as episodic events can be important drivers of the nutrient load arriving in the receiving environment. Episodic events are a part of life and it is our responsibility to manage the land and rivers to accommodate them.

10.4 COMPARING SCENARIOS

Some regional councils consider that for their application, the accurate prediction of absolute nutrient losses is not essential because regulations rely on relative comparison of nutrient loss estimates (see 2.2) (Environment Canterbury, 2020; Waikato Regional Council, 2020). Overseer has no estimation of error in its results (although we note that anecdotal estimates are sometimes quoted; Ledgard and Waller, 2001).

It would be convenient to assume that the comparison of two Overseer scenarios would show the same direction of change that we would expect to occur in practice. However, based on our assessment of the model structure and behaviour, we see no basis for this assumption. [28] For example, consider changing stock feed to something that has been observed to result in greater partitioning of excreted nitrogen into dung as opposed to urine. If Overseer does not specifically include losses from ammoniacal nitrogen and dissolved organic matter due to dung depositions, it may estimate lower nitrogen leaching. Furthermore, for some landscapes these surface flows may be the dominant nutrient losses (as discussed in 8.1.2). In addition, it would be important to understand how plant growth would be affected by these changes and how the different scenarios would respond to climate variability.

In summary, scenario comparison is only justified if there is confidence in the model structure and its ability to capture possible system responses. This includes the impact of climate variability on different scenarios, and the interactions between different model components as they are affected by the scenarios.

10.5 IMPLICATIONS FOR REGULATION

A key requirement of the use of Overseer in regulation is its ability to give reasonable estimates of long-term average nutrient losses from agricultural enterprises to help guide regulatory decisions as listed in 2.2. Guidance to regional councils (Freeman *et al*., 2016; Willis, 2018) notes that Overseer's estimates should be interpreted as long-term average nitrogen leaching rates (because Overseer uses 30-year average climate data) and it is best used to assess relative, rather than absolute, differences in nutrient losses.

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[28] This assumption does not apply to experimental data. There is a huge body of statistical theory that is applied to assess whether experimental observations are significantly different from each other.

As highlighted in 10.2, Overseer's structure, data, and behaviour suggest predictions of absolute and relative nutrient losses are likely inaccurate. In addition, nutrient losses vary from year to year and within years in response to climate variability. Average climate data and constant plant growth cannot be guaranteed to generate results consistent with the real world. A more accurate calculation of long-term average nitrogen leaching would be to average daily nitrogen leaching rates modelled using 30 years of actual daily climate data, as previously discussed (see 5.2, 9.2, Appendix Two).

10.6 IMPLICATIONS FOR DECISION SUPPORT

Decision support tools usually identify two main types of decisions: tactical and strategic. Tactical are generally short-term decisions such as how much fertiliser to apply in response to a soil test analysis, whether to cut pasture for silage, adjusting stock numbers in response to seasonal growth characteristics, and so on. Strategic decisions are more long-term and often relate to risk assessment; for example, for a dryland sheep enterprise, what stock numbers can be run with supplementary feed requirements not exceeding some threshold value? This example requires a long-term analysis to see how pasture and animal production vary in response to climate variability and whether a system is viable for the range of likely climate scenarios for the farm's location. Overseer was designed to support farmers with strategic decisions (Muirhead, 2020). One example of this is the management of FDE (see 2.3.1) or determining maintenance fertiliser requirements[29].

Once effective management strategies are known, Overseer provides a means of making comparisons of nitrate losses between these strategies. Such comparisons rely on confidence in the modelled output, which relies on climate inputs and model structure. Accurate climate inputs are important: if a farmer can reduce nitrogen losses from the system through a set of management decisions, how applicable is this likely to be for a range of different climate conditions? There also needs to be confidence in the model structure, and there are many areas where this is unlikely to be the case.

Overseer cannot be viewed as a decision support tool for investigating future scenarios or increasing productivity because it requires that production is known. It does give an estimate of nutrient dynamics for a given enterprise and associated management, but the model assumes all relationships between management decisions and productivity are known. As highlighted by Pinxterhuis and Edwards (2018), simple calculations based on readily available farmer information can provide much insight into efficiency of nitrogen use.

10.7 MĀTAURANGA MĀORI AND TE TIRITI O WAITANGI

Related to Overseer's use in regulation and decision support is engagement with Māori. Throughout model development, there was no engagement with Māori. This is symptomatic of wider systemic issues in Aotearoa New Zealand's science system. Neither the relationship Māori have with the natural world nor the role of Te Tiriti o Waitangi and related principles in decision support tools have been included in Overseer or contributed to its development. We understand that Overseer Ltd has more recently begun engaging with Māori (Overseer Ltd, 2020b). However, for a model to be used in regulation in Aotearoa New Zealand, it must engage with and learn from Māori from the beginning to ensure it reflects the Māori worldviews, incorporates mātauranga, and is useful to Māori land users. Indeed, this is a challenge for Aotearoa New Zealand's entire science community.

It is not for this report to speculate or prescribe how mātauranga should be incorporated into the development of a decision support tool. For Māori, mātauranga is a very personal form of knowledge and often has a local application which cannot necessarily be assumed to be suitable across all iwi or regions. It is therefore more appropriate to develop relationships between science and the Māori communities of interest which can drive knowledge-sharing and contribute to future tools. Building such relationships ensures consultation is possible, and that all parties can be comfortable with processes and outcomes – a collaboration of culture and science.

It is also apparent that Te Tiriti o Waitangi and its associated principles have not been considered in the ongoing development of Overseer. This is despite the commitment between Māori and Government to honour Tiriti principles. While many advocates look for statutory processes to support compliance around Te Tiriti o Waitangi obligations, it is more effective to build a process through the

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[29] Overseer does not model the response of plant growth to soil nutrient status which limits its ability to estimate fertiliser requirements. However, it can indicate whether too much or not enough fertiliser has been applied in a given year, which can inform adjustments for the following year (noting that it is not appropriate to use Overseer to model future scenarios).

aforementioned relationships with Māori to ensure the ownership of the final product is appropriately valued by all parties. Māori have an inherent role as kaitiaki over the land and water resources, so it is in their best interests to take the opportunity to contribute to the ongoing evolution of regulatory and decision support tools such as Overseer.

11 Conclusions

Waiho kia oroia, he whati toki nui. Let it be sharpened, it is a broken big adze.

There is no doubt that in Aotearoa New Zealand, current land use is causing excess nutrients to enter freshwater, causing harm (MfE & Stats NZ, 2020). The priority from a Māori perspective is protecting Papatūānuku (our natural resources). While this perspective is represented by Māori, it is a value shared by many New Zealanders. It is, therefore, important that tools like Overseer that have the potential to support kaitiaki are effective and can positively contribute to upholding the mauri and mana of Papatūānuku. Tools like Overseer have historically been used to assist in such environmental decision making.

In Chapter 1 we introduced our process, and the scope and objective of this review. Our aim was to assess whether Overseer's current modelling approach is fit-for-purpose to model nutrient flows within Aotearoa New Zealand farm systems, in the context of its current use as a regulatory and decision support tool. Our scope did not include assessment of the user interface nor the data files collated. These components may have utility in future endeavours to help landowners reduce nutrient loss from their properties. We also did not evaluate the effectiveness of Overseer in encouraging farmers to adopt nutrient management strategies. In Chapter 2 we discussed Overseer's history and current use. We found that based on its current use, we need confidence that Overseer's modelled outputs provide us with estimates of the direction and magnitude (and associated error) of the change in nutrient losses from a farm due to a change in farm management.

In Chapter 3 we introduced the Te Ao Māori and Te Tiriti o Waitangi interest in this work. For any regulatory or decision support tool to be fit-for-purpose for Māori, developers need to work in partnership with Māori to give effect to mātauranga Māori and Te Tiriti o Waitangi.

Chapter 4 provided a brief discussion of different model types, and our framework for model evaluation.

Chapter 5 gave an overview of Overseer's model structure, including its back-calculation of plant growth from user-specified farm production information, its use of average climate data, and its focus on nitrate which is only appropriate in limited landscapes. Chapter 6 discussed the animal metabolism model component, which generally appears fit for use in regulation in limited circumstances. Chapter 7 discussed the pasture, crop, and horticulture components. The pasture model highlights some of the practical advantages of the back-calculation approach, but this approach requires assumptions about utilisation – so further investigation is needed to determine whether we can have confidence in this approach. Our investigation of the crops component revealed the lack of mass balance and problems with the treatment of soil organic matter dynamics, which gives us a lack of confidence in model outputs from those enterprises. These problems were reinforced in Chapter 8 where we discussed soil water and nutrient dynamics. Furthermore, the use of single layer soil hydrology model and the range of issues with the modelling of nutrient dynamics limit our confidence in Overseer's nitrogen outputs across enterprises.

In Chapter 10 we returned to the framework we introduced in Chapter 4. Overseer's structural issues (its failure to simulate underlying biological, chemical, and physical relationships; and its lack of mass balance) can lead to inaccurate representations of system dynamics, which limits the confidence we can have in its outputs. Limitations with the quality of the data used in model development similarly impede the reliability of predictions. Discussions of model behaviour highlighted the issues presented by Overseer's macrostructure, including how the structure makes rigorous comparison with experimental data difficult. While there has been an emphasis on comparison of Overseer with experimental data as a means of assessment, such assessment cannot increase our confidence when such problems with the model structure remain.

Our core concerns are that Overseer:

- Is a steady state model attempting to simulate a dynamic, continually varying system;
- Uses monthly time-steps;
- Uses average climate data and, therefore, cannot model episodic events, or capture responses to climate variation;
- Does not balance mass;
- Does not account for variation in water and nutrient distribution in the soil profile;

- Does not adequately accommodate deep-rooting plants;
- Focuses on nitrate and omits ammoniacal nitrogen and organic matter dynamics; and
- Lacks consideration of surface water and nutrient transport, as well as critical landscape factors.

As a result of these concerns, we do not have confidence that Overseer’s modelled outputs tell us whether changes in farm management reduce or increase the losses of nutrients, or what the magnitude or error of these losses might be.

Future efforts to help understand, quantify, and reduce nutrient losses may include development of biophysical models, possibly in conjunction with simple decision support tools. There may be aspects of the Overseer model, such as its user interface, that can contribute to developing these tools. Decisions on the way forward will no doubt take into account many factors but should be driven by what will lead to the best outcomes for freshwater quality in Aotearoa New Zealand.

12 Appendix One: Inputs

Table 12.1 Overseer's inputs

	Description	Effect
Blocks	Blocks are areas of the farm with similar characteristics and management.	The definition of blocks is important to understanding the effects of different environments and management practices.
Soil	Users should define soils for each block. Each soil defines a set of properties that affect soil moisture, nutrients, drainage, etc.	Soil characteristics are a key input into the drainage model. They affect how water drains and the water holding capacity for plants.
Soil tests	Users can enter nutrient testing results for blocks.	Soil nutrient tests are used to initialise the nutrients in the soil before applying fertiliser, irrigation, rainfall, etc. They are principally used in the phosphorus model, and to estimate fertiliser maintenance requirements for each block. If soil test information is not entered, the model will use defaults based on soil inputs.
Climate	Data on average temperature, rainfall, and potential evapotranspiration for each block are obtained using 30-year average climate data for the location. Regional seasonality is used to extrapolate the annual average to monthly or daily values. The region or nearest town is set for each farm and is used for all analyses within the farm.	Climate is a key input into the drainage model. It affects evapotranspiration and biological processes such as decomposition, volatilisation and denitrification. Temperature and rainfall affect the shape of the urine leaching curve.
Pasture/crops	The user defines the pasture, crops or fruit grown on each block.	The defines the characteristics used in modelling uptake, residues, growth and nutrient transfers for pastures/crops.
Drainage system	The user defines whether blocks have a mole/tile, other or no drainage system, and how water is captured.	A drainage system diverts subsurface losses direct to the stream. This is important for consideration of mitigation options.
Animals	The user enters the animal enterprises on the farm as mobs of animals with similar characteristics (e.g., weight, age). The user defines the criteria for distributing animals across the farm.	Animals are a key driver of nutrient flows. The metabolisable energy requirements of the animals are calculated based on production and weight gain. These energy requirements are used to estimate pasture growth.
Supplementary feed imported, harvested, and fed	Users define any additional feed (harvested or imported) that is fed out on the farm. They describe which animal enterprises are fed and where.	Supplementary feed is used to calculate dry matter intake and hence the nutrient intake of animals.

Structures	The user defines animal structures on the farm (e.g., milking sheds, feed pads, wintering pads, standoff pads). They describe which animal enterprises are on the structures and for how long.	Structures determine where animals are, what they are fed, and what effluent is collected and in what way.
Wetlands	The user defines fenced-off wetlands as blocks, and wetland areas within other blocks.	Wetlands are used to model nitrogen capture from blocks on the farm. This does not affect block leaching numbers but removes nitrogen from the overall farm total.
Fertiliser	The user defines all fertiliser, lime, and organic material applied to blocks and the months when it was applied.	The nutrient requirements of plants are based on production (animal requirements for pasture or yield for crops). The nutrients available for plant uptake are determine from soil tests, fertiliser, irrigation, rainfall, and effluent. These nutrients accumulate in nutrient pools within the soil.
Effluent	The user defines the effluent management system applied to each structure. They describe how solid and liquid effluent are stored and the applications of effluent on blocks.	The system settings define the losses due to denitrification and volatilisation during collection. Effluent adds nutrient to the land which may be taken up by pasture.
Irrigation	The user defines the type of irrigator, the approach to monitoring, and the months that irrigation is applied.	This is used to determine any losses during irrigation. It also determines the depth of water applied.
Greenhouse gas settings	The user has the option to override the default settings for fuel, fertiliser applications, transport and electricity use.	This affects the embodies carbon dioxide emissions.

13 Appendix Two: Climate and time-steps

Two core characteristics of Overseer are the use of average climate and monthly time-step for all processes except soil water dynamics. Soil water dynamics calculations use a daily time-step but calculated variables such as drainage and runoff are aggregated to monthly values which are used for other processes (e.g., leaching). The climate data were supplied by NIWA, although users can enter data themselves. However, there is no facility to enter daily climate data. The data supplied by NIWA have been calculated from daily climate data for 1981-2010, with location-specific data calculated by various extrapolation processes based on actual available data. This type of extrapolation is now quite common.

We raise three basic questions in relation to climate data:

1. Why use averages when actual data are readily available?
2. Why use a monthly time-step when daily data are readily available?
3. Is there such a thing as an 'average' year?

When Overseer was first developed, daily climate data were not routinely available. That is not the case now. These questions should therefore be redundant unless there are actual, practical advantages of not using daily climate data.

To address the questions above we obtained actual climate data from the NIWA Virtual Climate Station Network (VCSN) (see 9.2). These were for 1990-2020. We used these climate data to run some simulations using a simulation model (see below).

Pasture modelling – Ag360 project

The simulation model developed by one of the Panel members (Dr Ian Johnson) in Australia as part of the Ag360 project by the former Sheep Cooperative Research Centre and the University of New England in Armidale, New South Wales, Australia (www.ag360.com.au). Although the model was developed in Australia, it is reasonable to apply it in New Zealand. For example, Johnson *et al.* (2008) used the DairyMod/EcoMod model to analyse pasture growth rate data in both countries, and the models have structural similarities.

The Ag360 project is a web-based project that allows users to run pasture simulations for their properties using live daily climate data from 1986 to yesterday, using modelled 90-day projections. The model uses daily values for rain, solar radiation, maximum and minimum temperature, vapour pressure deficit, and windspeed. We used an average value for windspeed in this simulation, since in New Zealand actual data are only available from 1997. An important feature of the model is that it is fast so computational speed is not a concern when using detailed input data; the model will typically run a 30-year simulation in less than 0.5 seconds.

(We are not advocating for this model or any other. It is solely used since its structure lends itself to a simple analysis to look at the use of average and actual climate data in an agricultural system.)

The concept of using average climate data is useful for analysing of, for example, climate patterns, variability or change. However, in a simulation model, is using averages meaningful? Overseer aims to analyse an 'average' year. This is different from analysing all years than averaging the results. In non-linear systems the average of the system's responses to variable inputs may not be the same as the response with a single input represented by the average of inputs (Nonhebel, 1994). This is illustrated below.

Consider a simple response curve as illustrated in Figure 13.1 (curves like this are common in biological systems). This type of response is sometimes referred to as 'diminishing returns.' This example uses a simple equation known as the 'rectangular hyperbola.' This is the same form of equation used in the fertiliser response example presented earlier in the discussion of empirical models (see 4.1.1).

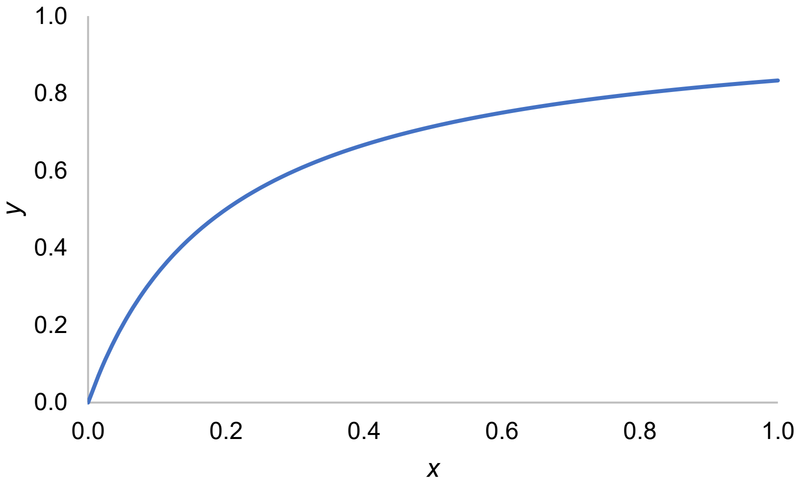

Figure 13.1 Simple 'diminishing-returns' response described using a rectangular hyperbola

Suppose an experiment measures the response (*y*) with inputs (*x*) in the range 0 to 1 in increments of 0.1. The average of the individual responses is 0.62. Now, the average of the inputs is 0.5 and evaluating the curve for $x = 0.5$ gives $y = 0.71$, which is 13.5% greater than the true average of 0.62. We cannot expect responses evaluated at the average input to give a true reflection of the actual average system response (see also Nonhebel, 1994).

It is, therefore, vital to understand climate and climate variability. While statements like 'quasi-equilibrium' (see Chapter 5) or 'average year' sound appealing, we must ask if they have much meaning or over what time frame are they relevant. Once we understand this, we can assess how appropriate the assumptions in the model area.

The following analysis is for a location on the Canterbury Plains halfway between Ashburton and the Rakaia River.[30] While deriving statistics of climate data is theoretically straightforward, episodic events such as rainfall present a challenge. For example, consider Table 13.1 below.

Table 13.1 Summary statistics

Mean	2 mm d^{-1}
Median	0 mm d^{-1}
Maximum	199 mm d^{-1}
Minimum	0 mm d^{-1}
Proportion of rain days	24%

A mean of 2 or median of 0 is not helpful when it only rains 24% of the time. If the model added 2mm rain per day, it is unlikely that the water would ever get more than a few millimetres into the soil profile. Since daily rainfall is not much use for statistical analysis, convention is to use either the year or month to characterise rainfall variation.

Annual rainfall data are shown in Figure 13.2. These totals are highly variable, ranging from 497 to 1039 mm yr^{-1}. This is a two-fold difference. The mean in 736 mm yr^{-1}.

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[30] -43.725, 171.775

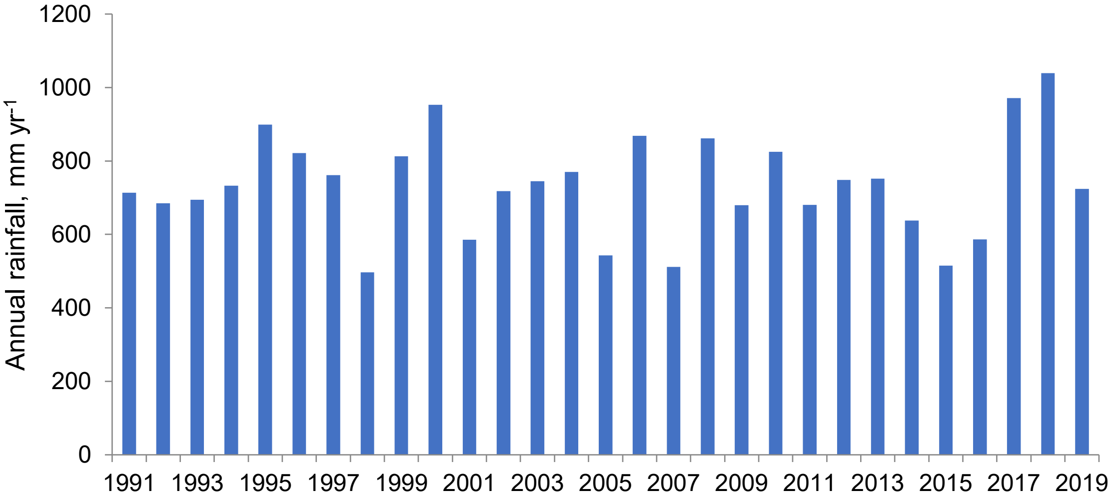

Figure 13.2 Annual rainfall

Just as annual rainfall is highly variable, so is rainfall distribution throughout the year. Figure 13.3 shows the monthly mean, median, minimum, maximum and 10, 25, 75, and 90 percentiles using a box-and-whiskers graph.

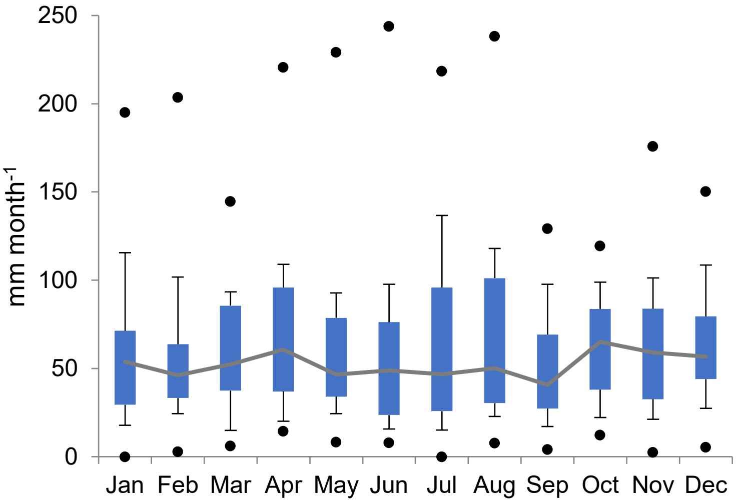

Figure 13.3 Monthly rainfall variability corresponding to Figure 13.2. The line is the median; the boxes are the 25 to 75 percentile range; the whiskers are the 10 and 90 percentiles; and the dots are the minima and maxima.

The illustration in Figure 13.3 gives insight into rainfall throughout the year:

- The median rainfall for each month does not vary much throughout the year.
- For all months there is considerable variation in rainfall. All months can have no rainfall or very high rainfall.

As we know from experience, rainfall can be variable.

Is there such thing as an average year? We ranked the years in order of total annual rainfall, identified the median year, and plotted the monthly rainfall values for this year along with two adjacent years. The median year was 1994 (732mm) and the adjacent years were 2019 (724mm) and 2003 (745mm). The monthly rainfall values for these years are shown in Figure 13.4. This shows that while the years had virtually the same annual totals, their rainfall distributions throughout the year were quite different. This emphasises that there is no such thing as an average year.

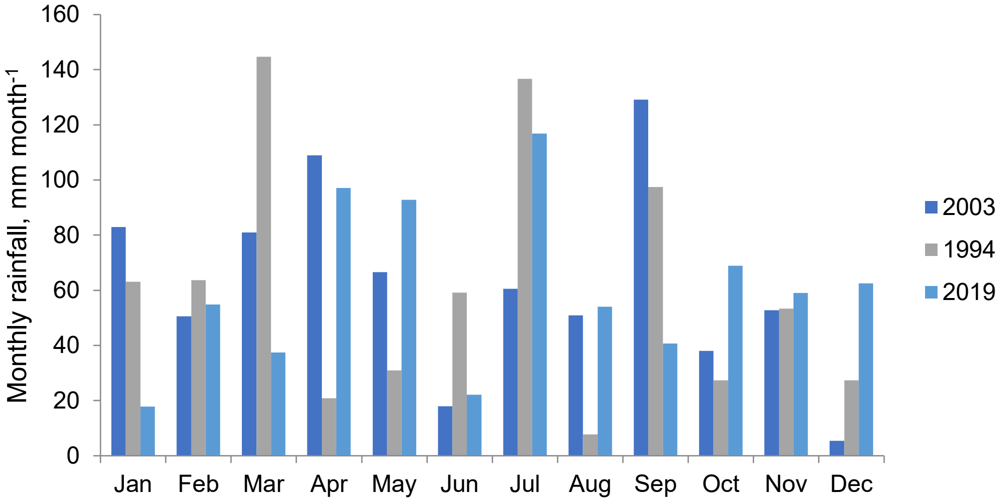

Figure 13.4 Monthly rainfall for the median and two adjacent years. 1994 had the median rainfall while 2003 and 2019 had the closest values to 1994

How is variation in climate data reflected in actual pasture growth? To look at this, the Ag360 model was used. The key characteristics of the pasture growth model in the Ag360 project are:

- It uses a daily time-step, with climate inputs for rainfall, solar radiation, maximum and minimum temperature, vapour pressure deficit, and windspeed;
- The model does not use a reference form of potential evapotranspiration (PET), but calculates it from underlying biophysics;
- The soil infiltration and drainage sub-model has multiple layers; and
- Drainage is reported at 1m.

The following example is for a generic well-fertilised pasture under a cutting trial according to the following:

- It is a good-quality productive pasture;
- It is a sandy clay loam soil (which is typically a moderately free-draining soil);
- Profile inclination is 5% (approximately 3°);
- The simulations do not consider responses to soil nutrient status, but it is assumed that the pasture is well-fertilised and nutrient availability does not restrict growth;
- Pasture is harvested to a residual of 750 kg ha^{-1} on the last day of each month. The total yield divided by the number of days in the month is taken as a representative value for the pasture growth rate in that month; and
- Annual cut yield is the sum of monthly harvests.

This type of simulation is intended to give a general snapshot of pasture growth rate characteristics. Growth rates are not calculated on the same pasture regrowth duration since days per month is not constant. Nevertheless, it is easy to analyse long-term simulation results to provide insights into system behaviour to inform more detailed studies.

Note that we intended to repeat this analysis with average climate data used in Overseer but were not provided the data.

Figure 13.5 shows the annual yields. The mean is 10.9 t ha^{-1} yr^{-1} (this is a dryland simulation), with minimum and maximum 5.1 and 16.1 respectively.

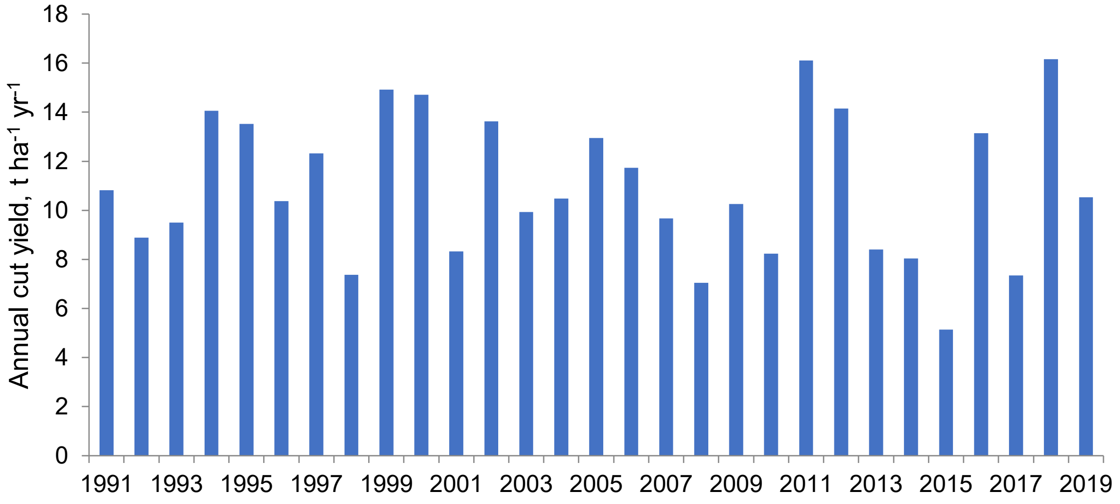

Figure 13.5 Annual pasture cut yields

The illustration in Figure 13.5 demonstrates the variability in yield in response to climate, particularly rainfall. To make some allowance for climate variability, experiments are often run for more than one year and typically over three years. Figure 13.6 shows the three-year rolling mean of the results in Figure 13.5. This rolling mean is still subject to variation, with minimum and maximum values 7.1 and 12.8.

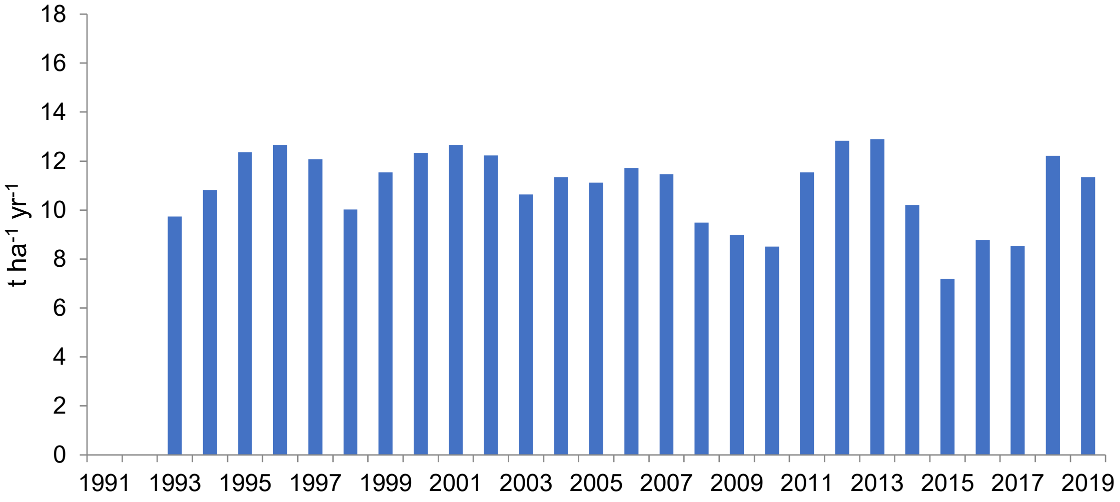

Figure 13.6 Three-year rolling mean for yields shown in Figure 14.5

We can take this averaging process a step further. Figure 13.7 shows the 10-year rolling mean. Variability starts to decrease, although the range is still 9.7 to 11.9. This is a range of 2.2 t ha^{-1} yr^{-1}, around 20% of the mean.

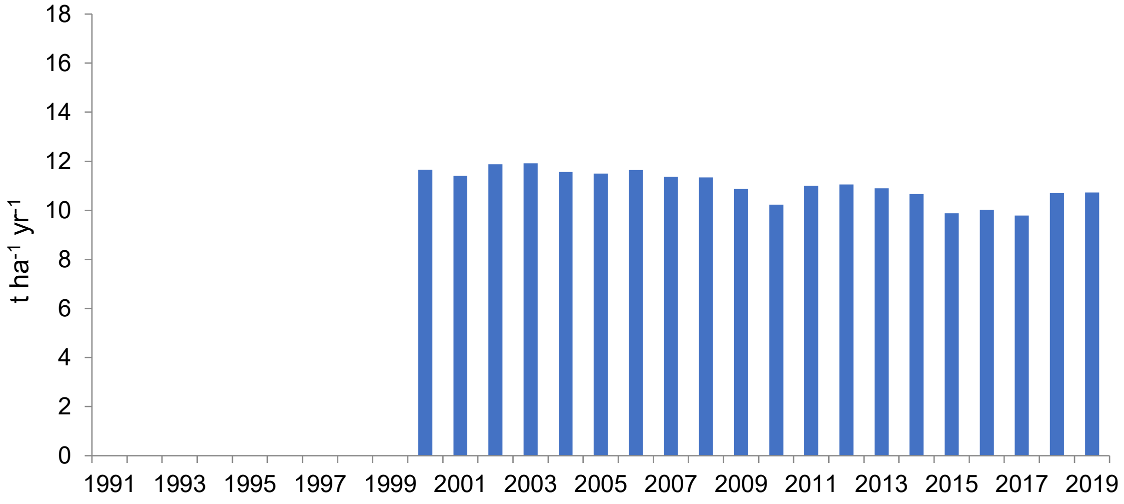

Figure 13.7 10-year rolling mean for yields shown in Figure 13.5

The monthly growth rate variability corresponding to Figure 13.5 is shown in Figure 13.8. Since monthly rainfall is so variable, so are monthly growth rates.

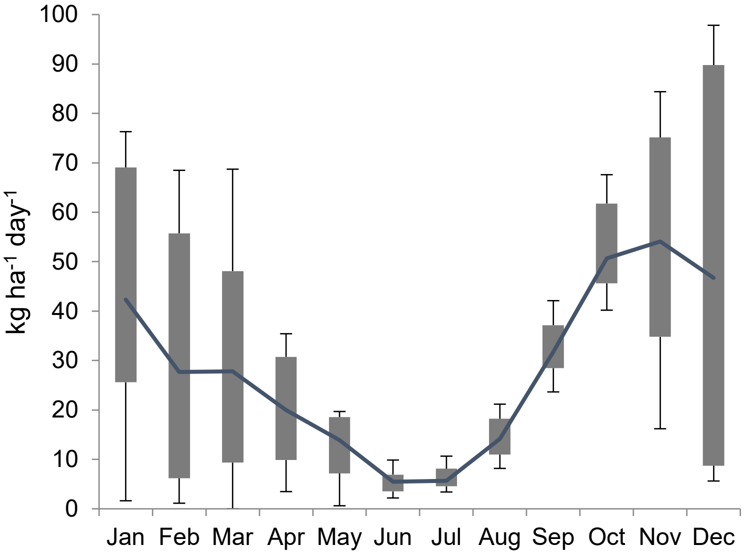

Figure 13.8 Monthly pasture growth rates for the cutting simulation. The line is the median; the boxes are the 25 to 75 percentile range; the whiskers are the 10 and 90 percentiles.

While yield is one aspect of system behaviour, one of the vital applications of our review is the regulation of nitrogen leaching. Leaching is closely related to drainage, so we will now focus on simulations of drainage. However, this model differs from Overseer in important aspects (the soil depth is 1m rather than 0.6m; the hydrology model uses multiple soil layers rather than the single-layer model used in Overseer; and all processes are modelled with a daily time-step). Figure 13.9 shows the annual drainage for the cutting simulations, along with the three-year rolling mean. Drainage is highly variable, ranging from 24 mm yr^{-1} to 503 mm yr^{-1} with mean 219 mm yr^{-1}. The three-year rolling mean ranges from 112 mm yr^{-1} (2014-2016) to 386 mm yr^{-1} (2017-2019) highlighted in red.

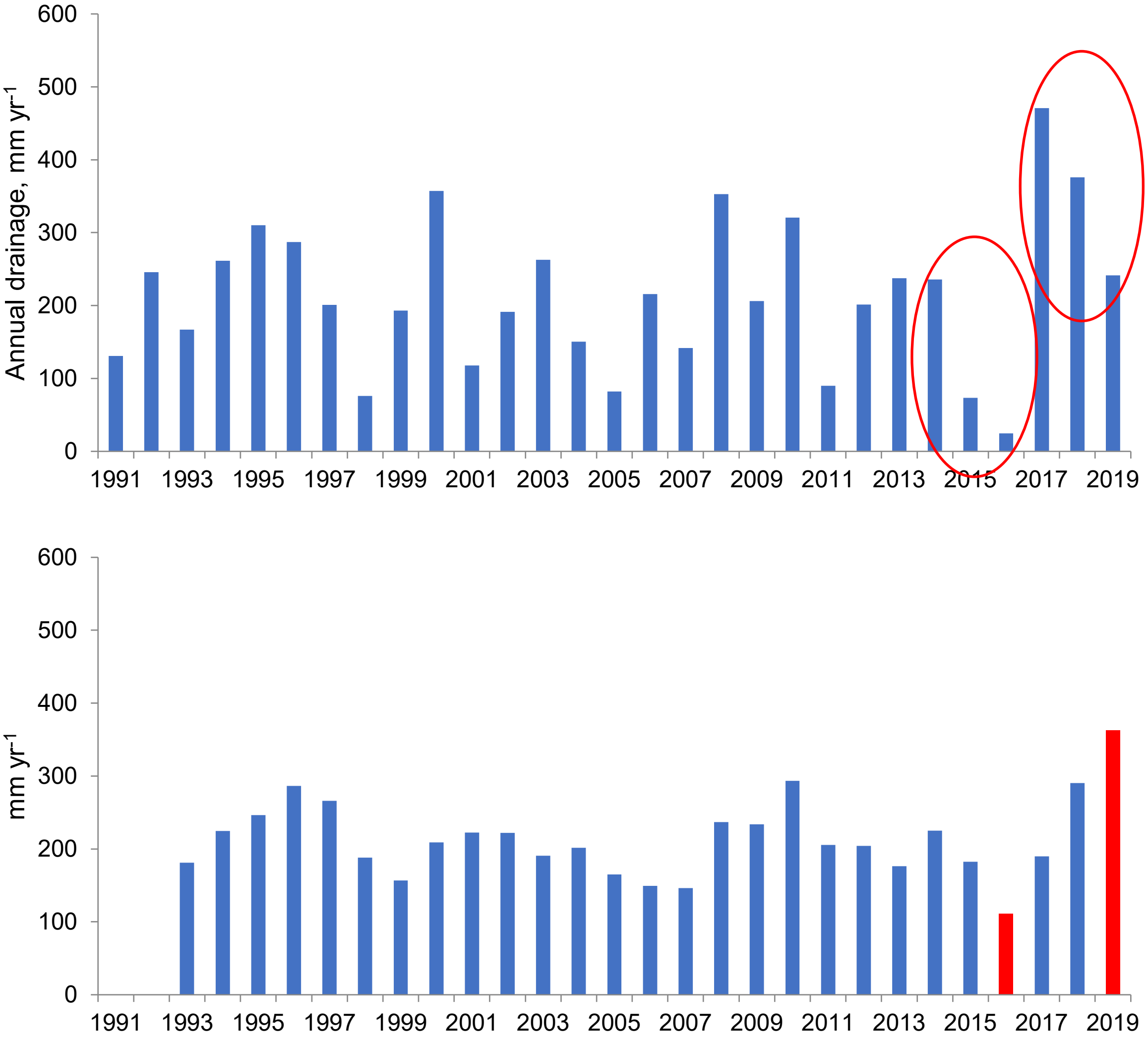

Figure 13.9 Annual drainage to 1m for the pasture simulation. Top: actual drainage; bottom: three-year rolling mean. The circled periods and red lines are discussed in the text.

Figure 13.10 shows the 10-year rolling mean for drainage (although few experiments run for this long). The results vary between 182 to 236 mm yr^{-1}. This is a difference of 25% of the mean; even 10 years may be insufficient to provide a true representation of average system behaviour.

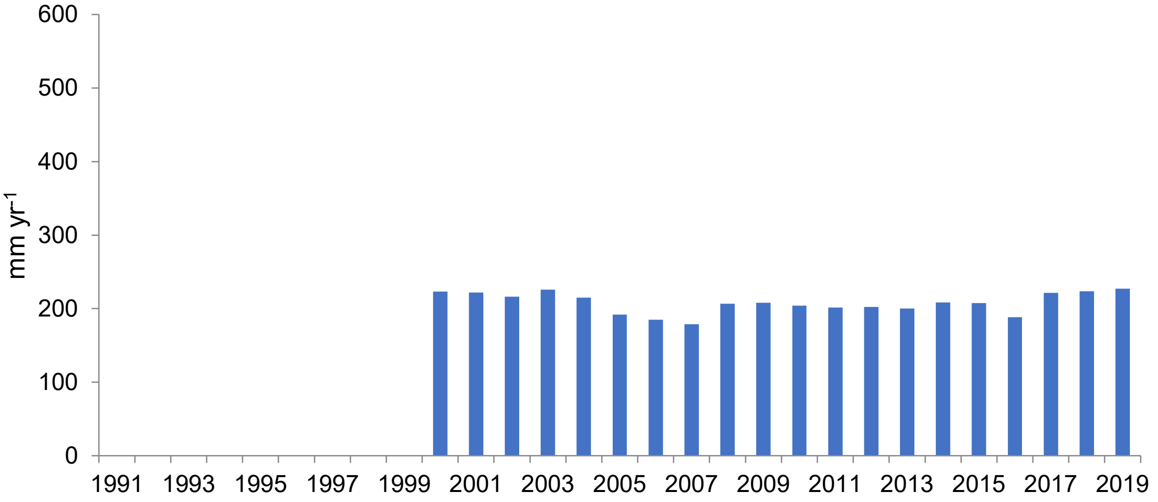

Figure 13.10 10-year rolling mean for the drainage results illustrated in Figure 14.9

These simulations use a 5% slope, which is relatively flat, so there was some runoff, although this is generally significantly less than drainage for freely draining soils on this type of profile. Nevertheless, it is instructive to look at runoff (Figure 13.11) which demonstrates the highly episodic nature of this aspect of the hydrology. For steeper slopes or heavier soils, runoff will be a significant component of the water balance.

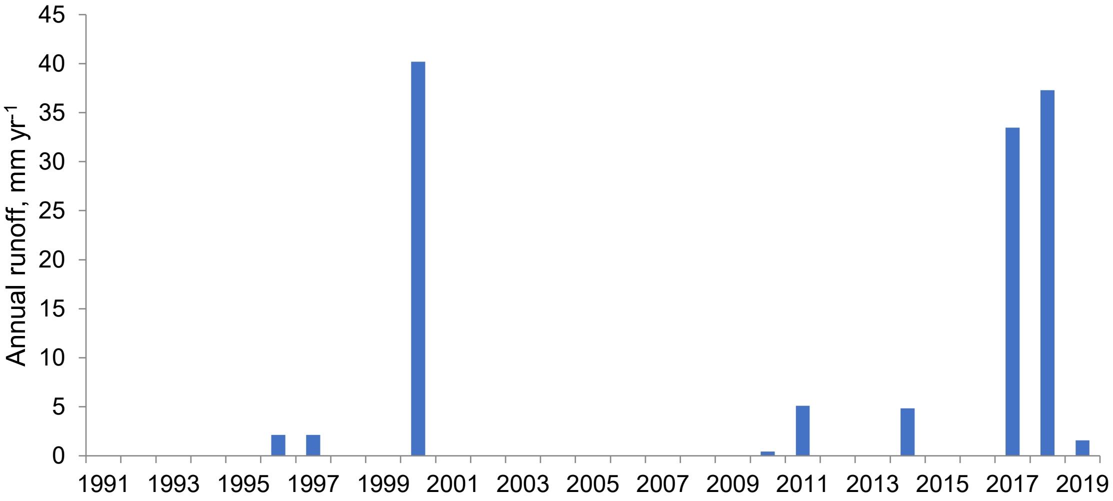

Figure 13.11 Annual runoff for the pasture simulation

As a final illustration of drainage characteristics, Figure 13.12 shows variation in monthly drainage rates corresponding to Figure 13.9. Monthly drainage is subject to large variation; there will be no 'typical' year. Interestingly, while the median rainfall is relatively constant through the year (see Figure 13.3), high drainage rates occur during late autumn to spring. This is due to the difference in evapotranspirative demands through the year.

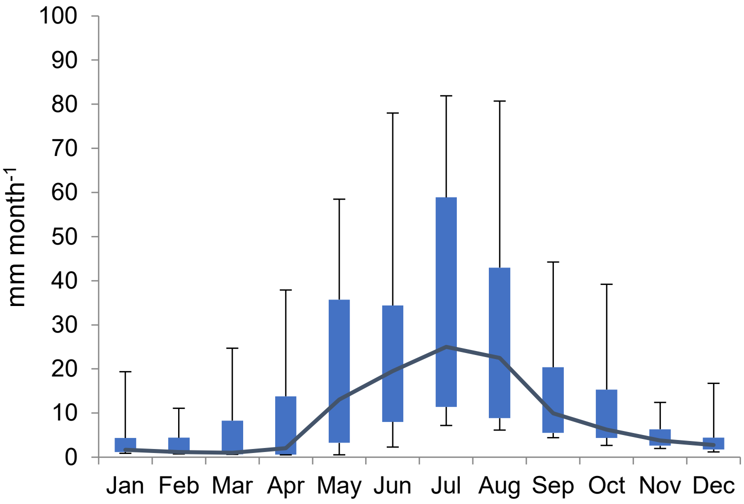

Figure 13.12 Monthly drainage rates. The line is the median; the boxes are the 25 to 75 percentile range; the whiskers are the 10 and 90 percentiles.

This analysis shows that there is no such thing as an 'average' year and that the concept of 'quasi-equilibrium' is unfounded. It is easy to analyse long-term simulations to understand the effects of management behaviour and other aspects of the system. There is nothing to be gained from averaging inputs; analysis should focus on outputs.

14 Glossary and acronyms

APSIM	The Agricultural Production Systems Simulator
CFAS	Computer Fertiliser Advice System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DM	dry matter
DMI	dry matter intake
DSSAT	Decision Support System for Agrotechnology Transfer
FDE	farm dairy effluent
FEP	Farm Environment Plan
FMU	Freshwater Management Unit
FSL	Fundamental Soils Layer
GCM	Global Circulation Model
GMP	good management practices
hikoi	step (sometimes to march in protest)
IPCC	Intergovernmental Panel on Climate Change
kaitiakitanga	the act of guardianship of our natural world to maintain its mauri
kaupapa	purpose
LAWA	Land, Air, Water Aotearoa
LUCI	Land Utilisation and Capability Indicator
mātauranga	traditional Māori knowledge
mauri	an expression of the 'life principle'
ME	metabolisable energy
MfE	Ministry for the Environment
MPI	Ministry for Primary Industries
NCE	nitrogen conversion efficiency
NDA	nitrogen discharge allowance
NIWA	The National Institute of Water and Atmospheric Research
NMP	nitrogen management plan
NNN	nitrate-nitrite nitrogen
OMD	organic matter digestibility
PCE	Parliamentary Commissioner for the Environment
RMA	Resource Management Act 1991
rohe	district, region, territory, area
SGS Pasture Model	Sustainable Grazing Systems Pasture Model
taha tinana	physical realm
taha wairua	spiritual realm
taha whānaunga	family realm
taha hinengaro	intellectual realm
Te Ao Māori	the Māori world
Te Ao Mārama	the world of light and the one in which we now live
Te Kore	the vast emptiness
Te Pō	the long night
Te Taiao	the natural environment
te whare tapa whā	the four cornerstones/realms of Māori wellbeing
tikanga	cultural best practice (Māori)
UNFCCC	United Nations Framework Convention on Climate Change
VCSN	Virtual Climate Station Network
whakapapa	genealogy/genealogical relationships
whenua	land in all its forms

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