Assessing the Total Impact of TomKat Ranch

Research and methodologies

November 2015

Contents

1. Introduction

This document explains the methodology applied to assess the total impact of TomKat Ranch's beef production system. This section describes the basis of total impact measurement and provides an overview of the project scope.

1.1. Basis of total impact measurement

Total impact measurement & management (TIMM) is a holistic approach to 'impact' measurement which uses a wide range of impact quantification and valuation methodologies to measure and value consistently the impacts of a given activity or organization.

By assigning a monetary value to each impact, different impacts can be compared, enabling management to assess the trade-offs of alternative strategies and investment choices in terms of their total impact. Crucially, all TIMM valuation methodologies adhere to the same underlying conceptual and economic underpinnings, primarily defined in welfare economic theory. This common conceptual framework means that all values either measure changes in human welfare[1] directly or use the best available proxies for changes in human welfare.

All of our impact measurement and valuation methodologies are based on well-established techniques and most have been applied in some form by national government agencies and global policy organizations including the European Commission, the World Bank and the OECD. The methodologies used to quantify and value environmental impacts are based on the latest academic research. They underwent an academic peer review in 2011[2] and have since been developed further based on input from the academic and expert practitioner communities. Most recently, following an independent review, they were accepted by the Natural Capital Coalition to form part of the basis for the Natural Capital Protocol (NCP). The NCP is a global, multi stakeholder open source platform supporting the alignment of methods for natural and social capital valuation in business. Its purpose is to transform the way business operates through understanding and incorporating their impacts and dependencies on natural capital[3].

1.2. Project purpose

The US consumes over 24 billion pounds of beef every year[4] and its cattle ranching industry generated $44 billion[5] in revenues last year. In recent years, there have been increasing concerns about the strain of beef production on natural resources. TomKat Ranch's goal is to produce beef in a way that makes it healthier for humans and for the planet. TomKat has undertaken a TIMM analysis to better understand the environmental and social impacts of its approach to beef production relative to 'business as usual' ranching in the US. To do this, this project considered the impacts of three different operating options:

- **TomKat Today**: TIMM analysis of TomKat Ranch's current operations, based on currently available TomKat data and secondary evidence as required.

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[1] Also referred to as 'well-being' in some contexts.

[2] See "An Expert Review of the Environmental Profit & Loss Account", PPR (2011). http://www.kering.com/sites/default/files/e-plreview_final-for_publicationwebsitefinal_final_1.pdf

[3] http://www.naturalcapitalcoalition.org/

[4] 2014 beef consumption in US from http://www.ers.usda.gov/topics/animal-products/cattle-beef/statistics-information.aspx

[5] http://www.beefusa.org/beefindustrystatistics.aspx

- **TomKat Tomorrow**: TIMM analysis of projected operations in 2040 – based on a projected future state where the TomKat production system is delivering closer to its full potential.
- **Counterfactual**: TIMM analysis of conventional ranch operations ('business as usual') based on a recent peer reviewed paper (Stackhouse-Lawson et al. 2012) that provides details on conventional cattle ranches in California.

1.3. *Project scope*

The project scope covers the impact areas and value chain elements that are most relevant to TomKat Ranch's dual purposes of beef production and land restoration. These were identified through a series of workshops with TomKat Ranch and Point Blue staff and validated with secondary research (e.g. lifecycle assessment studies).

1.3.1. *Impact areas*

The impact areas considered in the TIMM analysis are explained in Table 1.

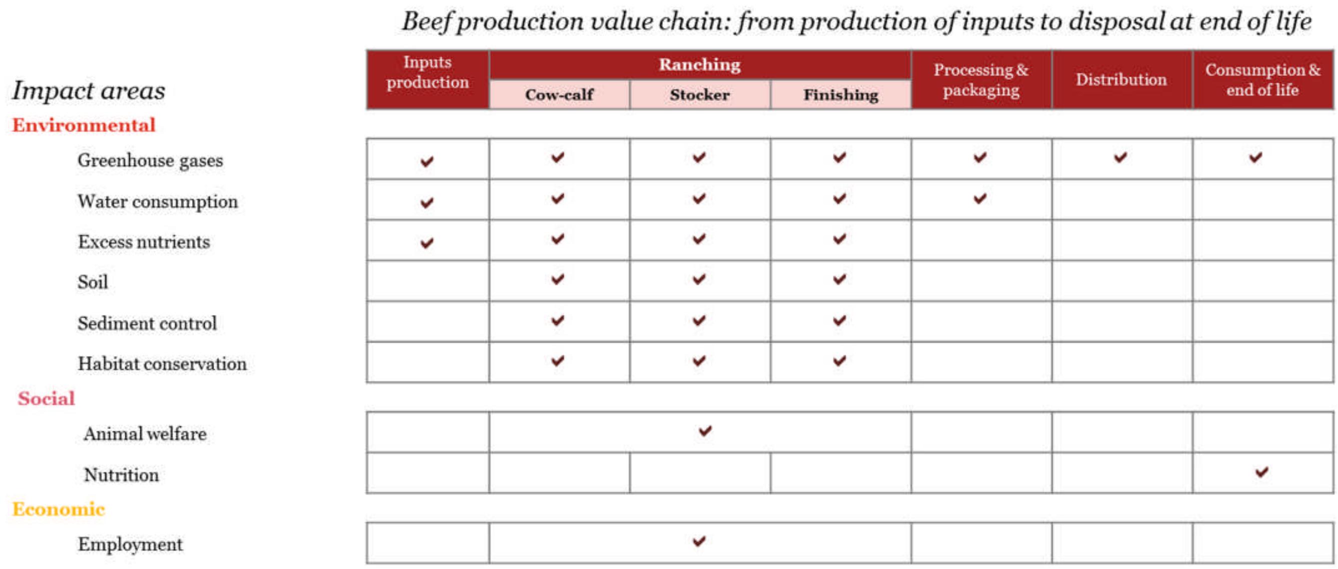
Table 1: Impact areas covered in TIMM analysis

Impact		Definition
Greenhouse Gases (GHGs)		Quantity and societal value of GHGs (carbon dioxide, methane and nitrous oxide) released into the atmosphere or sequestered as a result of value chain activities
Water consumption		Quantity and societal value of water consumed as a result of value chain activities
Excess nutrients	Phosphorus	Quantity and societal value of phosphorus released into the environment as a result of value chain activities
	Nitrogen	Quantity and societal value of nitrogen released into the environment as a result of value chain activities
Soil improvement		Societal value increase in productivity of soil due to intensive rotational grazing
Sediment control		Societal value of reducing sediment levels in Pescadero watershed
Habitat conservation		Societal value of wildlife in areas of ranch that have been preserved
Animal welfare		Additional premium customers would pay for the improved treatment of animals compared to conventional cattle rearing
Nutrition		Additional nutritional benefits (e.g. calorie reduction) of grass finished beef compared to the grain finished beef of the counterfactual
Employment		Wages paid to ranch employees

1.3.2. *Value chain*

Figure 1 shows the coverage of impact areas across different elements of the value chain. Coverage was determined based on materiality and relevance. For example, TomKat has the greatest influence on its direct impacts i.e. those relating to Ranching activities. We have therefore analyzed the full range of impacts for the Ranching phase. Increasing awareness of climate change among general public and interest in GHG footprint of beef mean we have considered GHGs across the entire value chain i.e. from 'cradle to grave'.

Figure 1: Coverage of impacts across the beef value chain



Beef production value chain: from production of inputs to disposal at end of life

Impact areas	Inputs production	Ranching			Processing & packaging	Distribution	Consumption & end of life
		Cow-calf	Stocker	Finishing			
Environmental							
Greenhouse gases	✓	✓	✓	✓	✓	✓	✓
Water consumption	✓	✓	✓	✓	✓		
Excess nutrients	✓	✓	✓	✓			
Soil		✓	✓	✓			
Sediment control		✓	✓	✓			
Habitat conservation		✓	✓	✓			
Social							
Animal welfare		✓					
Nutrition							✓
Economic							
Employment		✓					

Key

✓ Impact area considered in this element of the value chain e.g. excess nutrients are assessed at inputs production and ranching, but not for processing, distribution and end-of-life.

1.3.3. *Timescales*

The TIMM analysis considers 100 years of production to capture predicted changes in TomKat's production system over time, including changes in greenhouse gas impacts, soil carbon sequestration, on-ranch forage productivity, and water consumption. These manifest in the TomKat Tomorrow scenario.

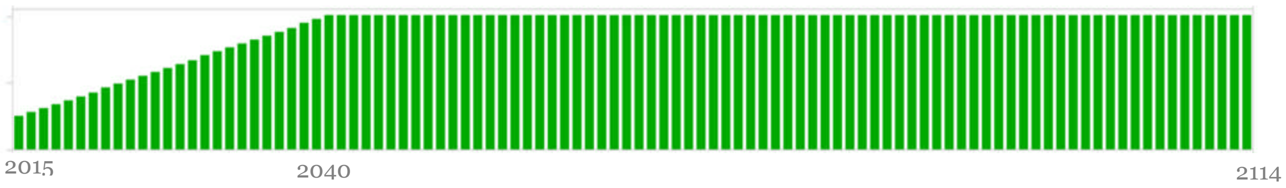
To model TomKat Tomorrow over 100 years, we:

- Modelled each impact in 2040 based on early data from TomKat ranch and additional secondary research, and assumed any changes between 2040 and 2015 occur linearly except soil carbon sequestration which is projected to increase gradually to around 2040 (see Section 4). After 2040, the impacts remain constant except for soil carbon sequestration which is projected to decline gradually to zero in 2075;

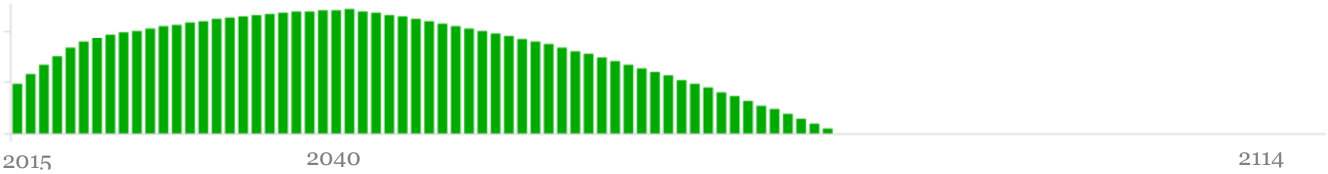
- Assume that no other management or exogenous changes occur.

Figure 2: Example impact changes over time: excess nutrients and soil carbon sequestration rate between 2015 and 2114

(1) Excess nutrients



(2) Soil carbon sequestration rate



Impacts in the Counterfactual and TomKat Today scenarios are held constant over time, apart from carbon sequestration in TomKat Today which remains constant to 2040 and then declines to zero in 2075. Alternative management options (e.g. composting), and exogenous changes (e.g. climate change) are each analysed separately as additional scenarios.

Time 'discounting' is used to express results over time in 'present value' terms by applying a societal discount rate of 3%[6]. Discounting is common practice in business and economics, however, views on appropriate societal and intergenerational discount rates do vary.

All present value estimates are expressed in 2015 USD.

1.4. Functional unit

To enable comparison of TomKat Ranch impacts with those of the counterfactual (which is at a much larger scale), results are presented using a functional unit of one pound (lb) of hot carcass weight (HCW). The HCW only includes the parts of the animal consumed. We assume a ratio of HCW to shrunken body weight (SBW) of 62% (Stackhouse-Lawson et al. 2012). Where not comparing with the counterfactual, it is more intuitive to consider impacts at an entire Ranch-level, so results are presented at the Ranch-level.

1.5. Document structure

The rest of this document summarizes the research undertaken, assumptions made, and methodologies used to quantify and value each of the different environmental and social impact areas within the scope of the analysis. It is structured into six additional sections.

Sections 2 to 5 were originally drafted as separate 'Decision Briefs' covering key data elements of the analysis. The TIMM assessment involves gathering together significant amounts of data from a range of primary and secondary sources, and using multi-disciplinary models and techniques to quantify the magnitude of the associated impacts. As a result, the assessment requires assumptions and judgments about certain technical and non-technical issues. Each Decision Brief was designed to: (1) explain a particular issue and related sub-issues; and (2) present the approach taken with supporting research and rationale, as well as other approaches considered. Research to support the approaches taken is drawn from an extensive, but not necessarily exhaustive, web-based review of relevant academic and industry literature; and where noted, consultation with external experts.

Sections 6 and 7 describe the valuation methodologies applied to the environmental and social impact areas, respectively. These summary methodologies are further supported by detailed and comprehensively sourced methodology papers for valuing environmental impacts available online at www.pwc.co.uk/naturalcapital.

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[6] 3% is the central social discount rate identified by the USEPA for its Social Cost of Carbon; this discount rate is also representative of the US Consumption Rate of Interest.

Section 8 summarizes research gaps identified in the course of this assessment which would improve the accuracy of the results, particularly in terms of quantification of impacts and future impacts of rotational grazing.

2. Quantification of whole-farm GHG and water impacts

2.1. Summary

2.1.1. *Key question addressed*

What are the most appropriate methods to quantify the greenhouse gas (GHG) emissions, water consumption and excess nutrients of TomKat Today, TomKat Tomorrow and the counterfactual?

The preferred sources of data for quantifying impacts are primary measurements in the first instance supported by peer-reviewed secondary research. However, our research shows that primary and secondary data will not be sufficient in this project due to the complex biological and physical processes associated with beef production:

Definitions

"TomKat Today": Environmental outcomes observed today at TomKat Ranch which reflect some early results of the 'intensive rotational grazing' cattle ranching system which was introduced in 2012.

"TomKat Tomorrow": Projected environmental outcomes in 2040 expected to result from the continued application of intensive rotational grazing at TomKat ranch until that date.

- Greenhouse gases: Reliably quantifying farm-level GHGs is difficult due to the complex relationships between farm inputs, activities and emissions (Del Prado et al. 2013). It would be expensive, technically difficult and time-consuming to take primary measurements to quantify actual GHG emissions. Moreover, GHG emissions of ranches are very site specific, so secondary research (such as GHG footprints measured at other farms) is unlikely to accurately represent our production system.
- Water consumption: Quantifying farm-level water consumption can be challenging due to varying definitions of water consumption and the number of different components related to the indirect water footprint of the feed and the direct water footprint related to the drinking water and service water consumed (Mekonnen & Hoekstra, 2010). Additionally, we and our counterparts have performed limited direct measurement of inputs so primary and secondary data are insufficient.
- Excess nutrients: Estimating cradle to gate non-point water pollution sources is challenging, especially with regards to quantifying the amount of excess nutrients reaching the water course. To date, very little primary and secondary data are available for purchased feed, with no data available on either standard crop inputs (such fertilizer, pesticide et al.) or calculated runoff quantities.

Modelling approaches and predictive tools exist to overcome these data gaps, but their use introduces additional uncertainty. There will be a necessary balance between primary measurement, secondary research and modelling approaches to produce a representative environmental inventory.

Our response to the central question above is structured as follows:

- The remainder of Section 2 summarizes why we believe the Integrated Farm System Model (IFSM) is the most appropriate model for fulfilling GHG and water modelling requirements;
- Sections 2.2, 2.3, and 2.4 discuss specific considerations for GHGs, water consumption, and excess nutrients, respectively. For each impact, we consider alternative approaches to modelling (sections 2.2.1, 2.3.1, and 2.4.1), followed by impact-specific limitations of IFSM and how we propose to address them.

2.1.2. *Recommendation*

Summary: We recommend that the Integrated Farm System Model (IFSM) is used to fulfill the modelling requirements for cradle-to-farm gate GHG emissions, water consumption and excess nutrients on the basis that it: (1) is credible to both the cattle industry and academics; (2) offers the appropriate balance between accuracy and flexibility; and (3) is a single integrated model that will offer consistency between impact areas.

The use of IFSM relies on providing data on a significant number of input parameters relating to cattle, soil, crop, and farming practices. These data needs will be met (in order of preference) by: (1) primary data; (2) secondary data from academic papers or industry publications; and (3) assumptions proposed by TomKat staff and partners and validated by external expert reviewers.

However, it is not appropriate to use IFSM to model all sources of GHG and water impacts. For improved accuracy, we will use primary data where possible instead of IFSM e.g. for quantifying GHGs associated fuel and electricity consumption. IFSM also has certain limitations: for example, some sources and sinks are not covered by IFSM (including soil carbon sequestration), so alternative approaches to measuring or estimating these are required. Thirdly, in some cases IFSM does not produce sufficiently detailed outputs to apply meaningful valuation approaches e.g. IFSM does not estimate the source of water consumption. Further discussion of the limitations of IFSM can be found in sections 2.2.2, 2.3.2, and 2.4.2.

We will take these limitations into account when deciding where IFSM will and will not be used. These decisions are summarized in the table below. A more detailed version of the table for each impact area can be found in appendices A2, A3, and A4.

Impact area	Modelling requirement to be met by IFSM	Areas that will not be modelled with IFSM
GHGs	• GHGs from cattle and manure • Nitrous oxide emissions from (on farm) pasture • GHGs from production of purchased feed and seeds	• Net soil carbon sequestration/emissions over time – this is not modelled by IFSM, so will be estimated separately (see Section 4). • GHGs from production and consumption of fuel and electricity – these will be based on TomKat data on actual fuel and electricity usage • GHGs from transportation of feed, animals, and meat – these are not included with IFSM so will be estimated separately using actual TomKat data on vehicle/fuel usage and data from lifecycle assessments (LCAs).
Water consumption	• Volume of cattle drinking water consumption[7] • Volume of water used to produce purchased feed and seeds	• Sources for water will be based on information found in the literature, except when primary data are available. • Soil water storage - this is not modelled by IFSM, so will be estimated separately (see Section 4). • Operational water use - this will be based on TomKat data on actual usage.

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[7] IFSM uses equations from Beckett & Oltjen (1993) to predict water consumption. Different equations are used depending whether the animal is a lactating cow, a non-lactating cow, or a growing animal. These take into account monthly average ambient temperature, as well as the water intake that is consumed from feed. The model also assumes a small amount of water is used for cooling when the maximum daily temperature exceeds 25 degrees C.

		- Water consumed in the production and consumption of fuel and electricity – these will be calculated using resource use factors based on TomKat data on actual fuel and electricity usage.
Excess nutrients	- Amount of excess nitrogen and phosphorus produced from purchased feed - Amount of excess nitrogen and phosphorus produced from grazing cattle manure	- Nutrient retention – this is not modelled by IFSM, so will be modelled separately

2.1.3. *Rationale*

After conducting an extensive literature review, we believe IFSM best satisfies the modelling needs for our assessment for the following reasons:

IFSM is credible amongst our key stakeholders

- Credible to conventional ranchers: IFSM has been developed by the USDA. It is being used by the National Cattlemen Board Association (NCBA) in its ongoing impact assessment of the American beef industry (National Cattlemen's Beef Association 2014).
- Credible to academics: It has been used and referenced by academics, including Stackhouse-Lawson et al. (2012) , Di Vittorio et al. (2010); Crosson et al. (2011); and Olander & Haugen-Kozyra (2012).
- It has been subject to empirical testing and calibration. For example, Rotz et al. (2013) found that simulated feed production and use, energy use, and production costs were within 1% of actual records at a US Meat Animal Research Center (MARC) in Nebraska. Stackhouse-Lawson et al. (2012) found 'good agreement' between simulated and measured methane emissions across 5 animal groups (within 1 and 11%). Simulated dry matter intake and CO2 emissions were within 5 to 7% and 4 to 17% of actual for Angus cows. Additional validation of forage production has been undertaken by Corson et al. (2007).
- IFSM has a clearly written and generally well-referenced manual explaining model design, user specification, relationships and assumptions (Rotz et al. 2014). The model and manual have been updated periodically since the 1980s to reflect new developments in soil, water, crop, and livestock science and modelling.
- IFSM draws on recognized research and incorporates numerous sub-models. For example, its carbon and nitrogen cycling relationship are based on the relationships used in DAYCENT (see section 2.2.1 for more information). The relationships for water consumption were obtained from Beckett and Oltjen (1993).[8] Calculations on nutrients are based on EPIC, SWAT, and GREAMS (see section 2.4.1 for more information).
- The developer, Dr Al Rotz, has been responsive to our on-going queries.

IFSM has an appropriate balance between accuracy, flexibility, and data requirements

- IFSM is a process-based simulation, which is generally considered to be more accurate for modelling GHG of agro-ecosystems than alternatives such as LCA or emission factors (Del Prado et al. 2013).
- IFSM has a balanced focus on modelling soil, plant and livestock, and their interactions. Most of the other process-based models considered had a primary focus on either soil/plants or on livestock.
- It is designed for site/field-level rather than regional or national scale estimation of emissions.

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[8] Values similar to those obtained by Beckett and Oltjen (1993) were confirmed by Capper (2011) once adjustments were made to exclude the processing stage.

- It has a high degree of parametrization offers significant flexibility to incorporate expected changes for TomKat Tomorrow. IFSM can capture changes in management decisions (grazing practices, manure management, livestock) as well as environmental conditions (rainfall, temperature, soil health).

There are some limitations of IFSM and modelling in general to consider:

- Process simulation models tend to exhibit high uncertainty on soil N2O emissions, which can have a significant impact on overall GHG results (Del Prado et al. 2013).
- Rotz contends that, “the water use footprint calculated by IFSM should be used only as a general estimate of water use. There is variability among production systems as affected by climate and production practices, and these differences may not be fully accounted in this model.”
- Models necessarily simplify what is happening in the real world. No model is able to exactly represent all ecological processes that occur in reality. IFSM does not take into account the effects of soil microbiology, plant and animal biodiversity (e.g. only 1 species of cool-season grass can be modelled at a time), water infiltration rates, clay loam structure, and precipitation in terms of fog.
- IFSM does not model CO2 losses from soil erosion.
- We will not undertake an audit of IFSM or otherwise verify its accuracy. However, we will be able to validate some outputs and calibrate the model based on empirical data from TomKat e.g. comparing predicted purchased feed (hay) requirement with actual requirements.
- IFSM is a relatively complex model and has extensive input data requirements. We do not have primary data for all the input variables required by IFSM. Estimates will need to be used in these cases, relying on secondary research and/or default range of values from IFSM. We will conduct sensitivity analyses to understand the potential impacts of these estimates.

In summary, we find IFSM to be at least as credible as the best viable alternative approaches for each of the three impact areas we propose to use it for. While there may have been some merit in arguing for the use of a single integrated model even if this were not the case, it is reassuring to conclude that it is.

2.2. Greenhouse gases (GHGs)

2.2.1. Other approaches considered

There are three categories of approach for estimating livestock GHG emissions (Del Prado et al., 2013: 374):

1. **Process-based simulations:** These use mechanistic processes representing biogeochemical relationships to simulate GHG dynamics and are widely considered the most accurate of the three categories. They have the practical drawback that they require significantly more primary input data and often detailed model specification. IFSM falls into this category;
2. **Emission factors:** Emission factors are best used to describe reactions which exhibit limited variation (e.g. emissions of CO2e as a result of fuel combustion) and are also sometimes applied to products and production processes that are considered homogenous and relatively unaffected by local factors. Generic emission factors are not detailed enough to capture the effects of our management practices or ecological outcomes on net GHG emissions. For example, the NRC found that the EPA’s emission-factor approach for estimating air emissions associated with beef and dairy operations to be ‘inadequate’ (National Research Council 2003);
3. **Life cycle assessment (LCA):** In the absence of a major primary data gathering exercise, following an LCA approach would involve drawing from Lifecycle Inventory databases which record the results of previous ‘relevant’ LCA studies.

The accuracy or otherwise is therefore almost entirely dependent on the availability of relevant pre-existing studies. Since we know from our research that this is distinctly limited, it is likely that a pure secondary LCA approach would be little better than using generic emission factors for estimating on-farm net GHGs.
Some LCAs of beef distribute GHG footprint of raising cattle between beef and other useful products e.g. leather. We have not done this in this analysis because it is not part of TomKat's business model.

The table below summarizes our research into viable alternative process based models.

Model	Description	Comments
CENTURY/ DAYCENT/COMET-FARM (USDA, Colorado State, NRCS)	CENTURY simulates the dynamics of carbon, nitrogen, phosphorus, and sulfur for plant-soil systems[9]. It consists of sub-models for soil organic matter/decomposition, water budget, grassland/crop, and forest management. DAYCENT is a daily (rather than monthly) time-step version of CENTURY. COMET-FARM is an online tool that allows farmers to estimate their ranch carbon footprint relating to crops, livestock, and energy use. It relies on DAYCENT to estimate crop-related emissions.	CENTURY/DAYCENT focus on crops rather than livestock. The only cattle-related customization is the grazing intensity. Model use and parameterization is more difficult than IFSM as there is no user interface. COMET-FARM is 'user-friendly', but does not allow the user to customize plant or soil characteristics. Instead, it draws information from databases based on zip code so cannot reflect direct measurements. COMET-FARM does not come with a detailed manual so it is not possible to assess the appropriateness of relationships used to model livestock-related emissions. IFSM uses the same relationships as CENTURY/DAYCENT to model cropland emissions, so these results should be consistent. We can run COMET-FARM as a sense-check against the results from IFSM.

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[9] https://www.nrel.colostate.edu/projects/century/

DNDC / Manure-DNDC (University of New Hampshire)	DNDC models the biochemical relationships of carbon and nitrogen in agro-ecosystems. It can be used to predict crop growth, soil carbon dynamics, nitrogen leaching, and GHG emissions[10]. Manure-DNDC is a modification of DNDC to more accurately simulate biochemical processes associated with manure generated in livestock operations. It has been used to calculate GHG and ammonia emissions from Californian dairy farms (Salas et al. 2009).	Primary drivers for DNDC are climate, soil, vegetation and management (Li 2012), implying insufficient focus on livestock. Manure-DNDC is livestock-focused but is based on feedlot/barn-raised cattle, and may not be able to simulate grass-finished systems. It also lacks a readily available user guide or reference manual. Waldrip et al. (2013)compared ammonia emissions between DNDC and IFSM and found the models were in good agreement and were both useful in predicting actual emissions. Both models were significantly more accurate than the emission factors used by the EPA.
Environmental Policy Integrated Climate (EPIC)[11] (Texas A&M University)	Cropping systems model that simulates effects of management decisions on soil loss, water pollution, crop yields, nitrogen and carbon cycling, and nutrient flows for approximately 80 different crops.	Focus on crops rather than livestock. Does not model livestock-related emissions and lacks adequate forage and grazing livestock components. Cannot adequately simulate rotational and Planned Holistic grazing. NB: IFSM uses relationships from EPIC to represent runoff and leaching of organic and inorganic phosphorus (P).
Holos	Whole-farm simulation that models GHG	Model designed specifically for use in Canada. For example, only Canadian regional weather can be simulated.
APSIM (University of Queensland, CSIRO, State of Queensland)	The Agricultural Production Systems Simulator (APSIM) is a farm-level model of plant, animal, soil and management interactions to produce outputs such as crop and pasture yields, soil erosion loss, and climate change scenarios.[12]	Can only model a restricted number of crops and forests, which would not adequately represent our vegetation.
MITERRA-EUROPE (Wageningen University, European Commission)	Model developed to assess the effects of policies and measures on agricultural nitrogen losses and phosphorus balances at a country, regional, and European Union-level[13]. The model is based on existing economic and environmental models such as CAPRI and RAINS, supplemented with FAO and Eurostat databases.	Focus on Europe is not appropriate for our assessment. Furthermore, only designed to provide country or regional-level information, so not appropriate for a farm-level analysis.

2.2.2. ***Limitations of IFSM***

Soil carbon sequestration

IFSM does not account for potential changes in soil carbon. The impacts of soil carbon sequestration on net GHG emissions will therefore need to be calculated separately using sequestration potential referenced in the literature. This is addressed in Section 4.

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[10] http://www.dndc.sr.unh.edu/

[11] Previously known as Erosion Productivity Impact Calculator

[12] apsim.info

GHGs from fuel and electricity production and consumption

IFSM estimates on-farm fuel and electricity usage by requiring the user to provide various details about farm machinery and equipment (specifications, usage etc.). However, we have primary data on fuel and electricity usage.

Recommendation

It would not be appropriate to estimate fuel and electricity usage since actual data are available. We will therefore use actual data on fuel and electricity usage rather than IFSM's estimates. To maintain comparability with the counterfactual scenario described by Stackhouse-Lawson et al. (2012), we will use the IFSM's emissions factors to convert fuel and electricity production/consumption to CO2 emissions.

GHGs from transportation

IFSM does not cover GHG emissions associated with transportation of purchased inputs, movement of cattle, nor distribution of meat. These likely represent a material proportion of GHG emissions and should not be excluded from the analysis.

Recommendation

For transportation of cattle to and from leased properties and to the abattoir, and for distribution of meat to customers, we will use actual estimates of vehicle and fuel usage. We will use the IFSM's emissions factors to convert fuel production/consumption to CO2 emissions. We will follow the approach used by Stackhouse-Lawson et al. (2012), who assume that offsite hay is produced within or near California. They assign a transport emission factor of 0.2kg CO2e/kg (dry matter) of hay.

2.3. Water consumption

2.3.1. Other approaches considered

Alternative secondary research

The table below describes the most salient studies identified in the literature review.

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[13] http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport1663.1.pdf

Study	Description	Comment
Mekonnen, M.M. et al. (2010)	Provides a global green, blue and grey water footprints of different sorts of farm animals and animal products, distinguishing between different production systems.	Study does not provide sufficiently detailed descriptions of any of the systems modelled, making it difficult to judge comparability/relevance.
Rasby (2011)	Guidance provided to ranchers on the water requirements for beef cattle.	Simplistic table derived from an article by Winchester in 1956. Does not include irrigation.
Capper (2011)	Deterministic model based on the metabolism and nutrient requirements of the beef population was used to quantify resource inputs and waste outputs per billion kilograms of beef.	Shared drinking water consumption model with IFSM. Irrigation rates are based on national averages, and do not provide sufficiently detailed descriptions of any of the systems modelled.
Ridoutt, B (2014)	Lifecycle assessment of beef production system in Australia.	Differences in location and production approach make it less comparable.
White (2013)	Water use included the total drinking requirement of animal populations and crop irrigation requirement. Drinking water required for each animal population was calculated from a regression equation linking drinking water intake to ambient temperature, animal size, and various feed qualities (Meyer et al., 2006). The water use associated with cropping was calculated from total land use and irrigation requirements per hectare (USDA-NASS, 2007).	Study does not provide sufficiently detailed descriptions of any of the systems modelled, making it difficult to judge comparability/relevance. The production system studied was 'parameterized' to represent average management practices in the United States.
Dick (2014)	Lifecycle assessment of beef production system in Brazil.	Differences in location and production approach make it less comparable.
Ogino et al. (2007)	Lifecycle assessment of beef production system in Japan.	Differences in location and production approach make it less comparable.

2.3.2. *Limitations of IFSM*

Source of water

IFSM does not currently calculate the source of water, only the total volume of water consumed throughout cradle to gate beef production system. Sources for water will be based on information found in the literature, except where primary data are available.

Recommendation

For purchased feed production[14], we assume fields are irrigated without rain capture.

For cattle drinking water, sources are based off the CEMAR water report. Ten percent of volume is recovered rainwater, while 30% comes from onsite wells, and 60% comes from onsite springs.

For operational water use, sources are based off the CEMAR water report—with 100% of water coming from wells.

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[14] Purchased feed production includes hay from Azevedo (50% alfalfa, 16% oats, 16% wheat, and 16% barley). Also potentially included in these calculations is irrigation at Ano Neuvo.

For seed production, a municipal water source is assumed. This is unlikely to have a material impact on water consumption.

Water consumed to produce electricity and fuel

Production of electricity and fuel (for farm machinery and transportation) can involve significant water consumption. IFSM does not include water consumption associated with the production of electricity or fuel.

Recommendation

On-farm fuel and electricity use will be based on actual data. For transportation of cattle to and from leased properties and to the abattoir, for distribution of meat to customers, and for transportation of purchased feed, we will calculate fuel use using the same approach as used for GHGs.

For gasoline, we will use an average of 1.3 gal (5 L) of net water consumed per liter of gasoline[15] as suggested by Wu et al. (2009). For electricity, we will use the national weighted average for thermoelectric and hydroelectric water use which is 2.0 gal (7.6 L) of water per kWh of electricity[16] consumed at the point of end use as suggested by Torcellini et al. (2003).

2.4. Excess nutrients

2.4.1. *Other approaches considered*

Alternative secondary research for nitrogen and phosphorus loading

Study	Description	Comment
Environmental Policy Integrated Climate (EPIC)[17] (Texas A&M University)	Cropping systems model that simulates effects of management decisions on soil loss, water pollution, nitrogen and carbon cycling, and nutrient flows for approximately 80 different crops.	Focus on crops rather than livestock. Does not model livestock-related discharges and lacks adequate forage and grazing livestock components. Cannot adequately simulate rotational and Planned Holistic grazing. Note: In IFSM phosphorus processes are modeled using relationships from the Erosion-Productivity Impact Calculator (EPIC) and the Soil and Water Assessment Tool (SWAT) with modifications by

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[15] Wu et al. (2009) presents a range of values for net water consumption of 3.4–6.6 L/L gasoline based on a number of factors including age of oil well, production technology, and degree of production water recycling. For simplicity, we took the average value of the range for use within this assessment. The 5 liters of water per liter of gasoline represents the average of U.S. conventional crude, based on an assessment of three Petroleum Administration for Defense Districts (PADDs) that represent 90% of U.S. domestic onshore crude oil production and 81% of U.S. refinery output. These regions are: PADD II (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, Ohio, Kentucky, and Tennessee), PADD III (Texas, New Mexico, Arkansas, Louisiana, Mississippi, and Alabama), and PADD V (California, Alaska, Arizona, Nevada, Oregon, and Washington).

[16] This figure was calculated by dividing total consumptive water use by the power sector, by total power output. A United States aggregate figure is calculated via a weighted average. This is based on two main categories: thermoelectric and hydroelectric; and three regions based on the three main electrical grid interconnects: Western, Eastern, and Texas.

[17] Previously known as Erosion Productivity Impact Calculator

		Vadas et al. (2004) and Vadas et al. (2005) to better represent surface processes.
Soil and Water Assessment Tool (SWAT) (USDA Agricultural Research Service)	River basin scale model developed to quantify the impact of land management practices on water, sediment and agricultural chemical yields. The main components of SWAT include weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond & reservoir storage, crop growth & irrigation, groundwater flow, reach routing, nutrient & pesticide loading, and water transfer.	Focus on crops rather than livestock. Does not model livestock-related discharges. Note: In IFSM phosphorus processes are modeled using relationships from the Erosion-Productivity Impact Calculator (EPIC) and the Soil and Water Assessment Tool (SWAT) with modifications by Vadas et al. (2004) and Vadas et al. (2005) to better represent surface processes.
Groundwater Loading Effects of Agricultural Management Systems (GLEAMS)[18]	GLEAMS assumes that a field has homogeneous land use, soils, and precipitation. It consists of four major components: hydrology, erosion/sediment yield, pesticide transport, and nutrients.	GLEAMS is a field-size model and cannot be used directly at the watershed scale and is therefore not appropriate for use. Note: USDA-ARS developed SWAT by extending GLEAMS to basin scale
Swiss Agricultural Life-Cycle Assessment (SALCA-P) developed by ART	This model for recording phosphorus emissions takes account of losses through soil erosion, surface run-off and leaching into the groundwater.	Default values are used for chemical and physical soil properties. IFSM allows for more granularity in Nitrogen & Phosphorus calculations.
Hydrologic Simulation Program—FORTRAN (HSPF)	Simulation of watershed hydrology and nutrient water pollution for both conventional and toxic organic pollutants. HSPF incorporates watershed-scale ARM and NPS models into a basin-scale analysis framework that includes fate and transport in one dimensional stream channels.	HSPF does not consider non-point sources, such as animal manure and therefore is not appropriate for use.

The table above describes the most salient studies identified in the literature review.

2.4.2. *IFSM Limitations*

Heavy metals and toxins

IFSM does not include other common pollutants to water that are generated in small quantities in the cradle to gate beef production system. These are likely to represent a modest proportion of the emissions to water in our own production system (e.g. associated with petroleum based fuel production), but may have a somewhat larger potential cost in the counterfactual where additional chemical inputs are used.

Recommendation

We conducted a materiality assessment on pesticides' impacts for each crop identified as using pesticides. We considered select[19] active ingredients (from the five pesticide classes Organophosphates, N-methyl carbamates, Triazines, Chloroacetanilides, and Pyrethrins/Pyrethroids) released into water, using crop specific EcoInvent life cycle inventories (LCI). Quantities of emissions per kilogram of crop reaching the water course are established using Agroscope's life cycle

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[18] Developed as an extension to Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS)

[19] Selection of final list of pesticides for analysis will be based on the human toxicity linked to the active ingredients identified for each crop type.

assessment method, Swiss Agricultural Life Cycle Assessment (SALCA). SALCA calculates emissions into surface waters taking into account the input from mineral fertilizers, farmyard manure and pesticides. We found that the impacts were immaterial compared to the effect of excess phosphorus and nitrogen (see Excess Nutrients valuation methodology).

2.4.3. ***Adjustments for riparian buffers***

Borders of forest and scrub line the majority of waterways on TomKat Ranch. Such buffers have been shown to remove some pollutants from ground and surface water, resulting in a lower pollution load when the water joins the stream(Zhang et al. 2009; Mayer et al. 2007). This effect is not captured by IFSM, so additional adjustments have been made to reflect the value of the improved water quality that results from maintenance of buffers.

Mayer et al’s 2007 meta-analysis quantifies the relationship between the width of a buffer, the vegetation type, and its ability to remove nitrogen pollution. Zhang et al. 2009 published a similar relationship for phosphorus pollution. These formulas were applied to data for the watercourses at TomKat Ranch, taking into account the relative importance of each waterway by weighting for length, volume and duration (for intermittent seasonal streams). These calculations found that, on average across TomKat ranch, pollution of the watercourses is reduced by 85% for nitrogen and 86% for phosphorus thanks to the presence of riparian buffers.

We assume there are no riparian buffers in the counterfactual as the available evidence suggests that a majority of U.S. farms do not have buffers (Chesapeake Bay Program n.d.; Maille 2001; Simpson 2008).

3. Conventional ranching – the counterfactual

3.1. Summary

3.1.1. *Key question addressed*

What is the appropriate basis for a conventional ranch scenario (the 'counterfactual') to be used for comparison with alternative ranching systems including for example high intensity rest-rotational systems?

3.1.2. *Recommendation*

Summary: We recommend using the three-phase system described in detail in Stackhouse-Lawson et al. (2012) as the framework for the counterfactual assessment. Quantification of counterfactual GHGs will be based primarily on using the parameters specified in Stackhouse-Lawson et al. (2012). Quantification of other impact areas will be determined using secondary research and applied to the production system described in Stackhouse-Lawson et al. (2012).

We recommend that the conventional ranch scenario is primarily based on the '*representative beef production systems in California*' provided by Stackhouse-Lawson et al. (2012: 4,641). We will consider the Angus systems rather than the Holstein system because the latter concerns by-products of dairy production, which is not relevant to our operations. Among the two Angus systems, we recommend using the three-phase system in preference to the two phase-system for several reasons, but principally because it is the most common cattle ranching system in California (Stackhouse-Lawson et al. (2012)) and therefore the most logical counterfactual. Highlights of the two Angus beef systems can be found in Appendix A1.

Stackhouse-Lawson et al. (2012) will serve as the **framework** production system for the cradle-to-gate counterfactual assessment, and be the main source of information for the quantification of baseline GHGs impacts. Secondary sources will supplement the Stackhouse-Lawson et al. (2012) framework for the baseline estimates of other impact areas: water consumption, excess nutrients, and soil & biodiversity. Having a consistent underlying framework will help us to ensure that, while data are necessarily drawn from numerous sources, they fit together to describe a coherent and recognizable conventional ranch scenario.

3.1.3. *Overview of our rationale*

Note: Careful consideration of the implications of key assumptions made by Stackhouse-Lawson et al. (2012) is presented below in Section 3.2.

After conducting an extensive literature review, we believe the conventional beef production system described by Stackhouse-Lawson et al. (2012) provides a credible and practical basis for the counterfactual because it is:

- *Relevant*: the study is recent (published in 2012) and is designed to provide 'baseline emissions' for Californian beef production systems. In designing the study, the authors consulted beef researchers, UC Cooperative Extension advisors, and beef cattle producers;
- *Credible to academics*: the study is published in the Journal of Animal Science and has been cited 23 times according to Google Scholar. No significant negative criticism of its findings have been identified (as at Feb 20, 2015);

- *Credible to conventional ranchers*: Stackhouse-Lawson is Director of Sustainability Research for National Cattlemen's Beef Association (NCBA);
- *Consistent*: Stackhouse-Lawson et al.'s results are based on output from the Integrated Farm System Model (IFSM), which is the same model we intend to use to analyze some aspects of our own production system. This will allow for consistent comparison between the counterfactual and our production system;
- *Detailed*: the paper describes the simulated beef production systems in detail e.g. type of feed, where the feed is sourced, location of the ranches/feedlot, transportation etc. – see Appendix A2 for full list of characteristics.

3.1.4. *Other approaches considered*

Alternative secondary research

Table 2 below describes the most salient alternative studies identified in the literature review. While our recommendation is that Stackhouse-Lawson et al. (2012) is the most suitable candidate for the counterfactual framework for the reasons described above, we will consider the methodological approaches and results of the alternative studies identified in our analysis for benchmarking and comparison.

Table 2: Alternative studies for the counterfactual

Study	Description	Comment
Pelletier et al. (2010)	Some similarities to Stackhouse-Lawson et al. (2012). Uses lifecycle assessment to compare the cradle-to-farm gate energy use, greenhouse gas emissions, and ecological footprint of two feedlot beef production systems (one with and one without a stocker phase) and one grass-based production system. See Appendix A3 for overview of these systems.	Focused on Upper Midwestern US, where production strategies are not directly comparable to California (e.g. differences in type and source of feed).
Phetteplace et al. (2001)	Excel-based model to estimate greenhouse gas emissions from nine US beef and dairy livestock systems.	Study does not provide sufficiently detailed descriptions of the systems modelled, making it difficult to judge comparability and relevance.
Johnson et al. (2003)	Estimated greenhouse gas footprint for five different US beef production management strategies.	Uses a subset of the data from Phetteplace et al. (2001), and is similarly lacking in detailed descriptions.
Beauchemin et al. (2010)	Uses Canadian greenhouse gas model Holos[20] to estimate the carbon footprint for a conventional beef ranch in Western Canada.	Differences in climate, production approach, and local operating context make these studies less relevant.
Peters et al. (2010)	Combination of lifecycle assessment for direct emissions and input-output modelling for supply chain emissions for three farms in Australia (two beef and one sheep).	
Basarab et al. (2012)	Comparison of whole-farm greenhouse gase emissions with and without growth implants for a beef ranch in Canada.	

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[20] Holos is a whole-farm greenhouse gas calculator developed by the Canadian government with a similar interface to IFSM. However, Holos is not as customizable as IFSM. For example, users can only select climatic conditions based on one of the Canadian provinces, whereas IFSM allows users to upload their own weather files.

Ogino et al. (2007)	Lifecycle assessment of beef production system in Japan.
Casey & Holden (2006)	Lifecycle assessment of beef production system in Ireland.

Develop own counterfactual

A further option would be to develop a counterfactual scenario from scratch based on information from conventional Californian cattle ranchers and/or other experts. While this would allow us to specify all the parameters and assumptions for the counterfactual, the process would be labor-intensive. Furthermore, it relies on identifying appropriate ranchers and experts who are willing to give us the detailed information required. Relying on a single ranch or expert is unlikely to be representative. Undertaking a representative survey of many ranchers would be time consuming, costly and highly dependent on finding people with the right data and knowledge.

3.2. Key considerations

3.2.1. ***Location of ranches***

The cow-calf and stocker phases modelled by Stackhouse-Lawson et al. (2012) are in Tehama County and Shasta County, respectively, which have significantly different climates compared to our coastal California climate. Assumed physical characteristics, such as soil type and ranch topography, also differ. These climatic and physical assumptions affect outputs such as amount of forage produced and amount of offsite feed required, which ultimately impact total GHG emissions, water use and water quality. Therefore, a direct comparison between Stackhouse-Lawson et al.'s results and our assessments would reflect both differences in production approach and physical and climatic differences. To reflect only differences in production approach, we would need to adjust the counterfactual to mirror our physical and climatic characteristics at TomKat Ranch.

Table 3: Climatic and physical differences between ranch localities

Characteristic	Tehama County (Stackhouse-Lawson cow-calf phase)	Shasta County (Stackhouse-Lawson stocker phase)	Pescadero (TomKat Ranch[21])
Annual precipitation	36.8 inches	60.5 inches	26.8 inches
Temperature (°F)	60.9°F	55.5°F	57.5°F
Wind speed	21.13 mph	19.46 mph	13.08 mph
Soil type	Medium sandy loam	Medium sandy loam	Medium clay loam / Medium loam
Topography (% slope)	15 to 25	> 25	> 25

Source of climatic data: http://www.usa.com/

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[21] For consistent comparison, we have used the same data source for the climatic variables. The closest proxy for TomKat Ranch using this source is Pescadero, CA.

Recommendation

We recommend adjusting the Stackhouse-Lawson counterfactual for climatic and geographic differences to match those at TomKat Ranch. This will provide a like-for-like comparison, showing the differences between production systems holding climate and geography constant.

3.2.2. ***Two phase or three phase system***

There are two Angus beef production systems assessed in Stackhouse-Lawson et al. (2012): a two-phase system (cow-calf and feedlot) and a three-phase system (cow-calf, stocker, and feedlot). See Appendix A1 for an overview of these systems. One of these needs to be chosen for the counterfactual assessment.

Recommendation

We recommend that the three-phase system is chosen for the counterfactual because:

- Stackhouse-Lawson et al. (2012; 4645) state that '*California beef cattle production typically consists of a 3-phase system*';
- Research suggests that most beef production systems in the US include a stocker or back-grounding period rather than going straight from cow-calf to feedlot (Chiba 2014);
- We would like to be able to share the analysis with a range of ranchers, including those who operate only cow-calf, stocker, or finishing phases. Choosing the three-phase system for the counterfactual will maximize relevance.

3.2.3. ***Treatment of manure in feedlot***

Stackhouse-Lawson et al. (2012) estimates its feedlot phase emissions based on exporting 100% of its manure to other agricultural sectors.

Recommendation

We recommend assessing the GHG impact of manure in the feedlot phase of the counterfactual scenario. We will model GHG emissions using the Integrated Farm System Model (see Section 2 for additional details), which quantifies emission of carbon dioxide and methane emissions from housing and manure storage. Floors of housing facilities are a source of carbon dioxide emissions due to decomposition of organic matter in manure deposited by animals. Although not a major source, barn floor emissions should be included to obtain a comprehensive simulation of farm-level carbon dioxide emissions from all sources. Carbon dioxide emissions are modelled as a function of ambient barn temperature and the floor surface area covered by manure. Additionally, carbon dioxide emissions from slurry manure storage are predicted as a function of the volume of manure in the storage using an average emission of rate of 0.04 kg CO2/m3-day. During manure storage, the cellulose in the manure is degraded by microbes, with products of this process serving as substrates for methanogenesis. Daily methane emissions from manure storage are a function of the amount of manure in the storage, the volatile solids content, and temperature of the manure (IFSM Reference Manual v4.1).

3.2.4. ***GHGs of antibiotics/hormones***

Stackhouse-Lawson et al. (2012) do not include the GHG impacts for the production of antibiotics or growth hormones.

Recommendation

For completeness we propose to add GHG impacts associated with the production of growth hormones in the counterfactual, although we expect this to have only a small effect on total GHGs. Opio et al. (2013: 13) exclude the production of cleaning agents, antibiotics and pharmaceuticals assessment, citing limited contribution of the processes to the carbon footprint. We will use generic chemical life cycle inventory data for the production of growth hormones, as our review of the literature has not identify quantities in the literature for the production of either with regard to cattle.

With regards to antibiotics, we were not able to identify reliable data on the quantity of antibiotics typically used in the production of cattle. GHGs associated with antibiotics were therefore not included in the analysis.

3.2.5. *Mortality rates*

Stackhouse-Lawson et al. (2012) apply mortality rates of 6%, 2%, and 1.6%–2.8% during the cow-calf, stocker, and feedlot phases, respectively. No references or rationale for the chosen rates has been provided, but we understand that the scenarios were '*defined through consultation from beef researchers, UC Cooperative Extension advisors, and beef cattle producers*' (Stackhouse-Lawson et al., 2012: 4645). Our estimates that its cattle mortality ranges from 0 to 2%.

Recommendation

We do not recommend making any adjustments to the mortality rates assumed by Stackhouse-Lawson et al. (2012). This is because Stackhouse-Lawson et al.'s mortality rates are largely in line with literature identified (see Table 4), even if on the high side for the cow-calf phase.

Table 4: Cattle mortality rates in the literature

Study	Finding
Loneragan et al. (2001)	Averaged between 1994 and 1999, mortality rate of feedlot cattle in US was 12.6 deaths/1,000 cattle i.e. 1.26%.
Kelly & Janzen (1986)	Literature review examining the morbidity and mortality of calves immediately after transfer to feedlots in North America. Around 15–45% of calves require treatment for illness, and 1–5% die during this period. The most common cause of death was related to the respiratory system.
Perrin et al. (2011)	Analyzed the data recorded in the National Cattle Register from 2003 to 2009, including data on about 75 million cattle to provide reliable statistics of cattle mortality in France. The average annual mortality risk of animals over two years was 3.5% for dairy and 2.0% for beef cattle.
Beauchemin et al. (2010)	Assume 3% death loss for (feedlot) stockers and 1% death loss for backgrounders and finishers.

3.2.6. *Impacts not considered by Stackhouse-Lawson et al.*

Stackhouse-Lawson et al. are primarily concerned with GHGs. The study does not consider the other impacts which we will include in our assessment i.e. water consumption, water quality, soil & biodiversity, animal welfare, and nutrition, so we will require secondary research to quantify these impacts for the counterfactual. Our approach is summarized in the table below.

Table 5: Key assumptions/supplementary secondary data sources

Impact area	Approach for counterfactual
Soil carbon	We propose to assume that continuous grazing practiced in the counterfactual does not lead to increases or decreases in soil carbon stocks during the period of comparison. The literature is divided on this issue, with some authors finding that continuous grazing can increase soil carbon stocks, while other finding that it is detrimental. We recommend that the counterfactual remain neutral with regard to soil carbon stock, and will note this assumption in any reporting findings.
Water consumption	We propose to use Stackhouse-Lawson et al.'s IFSM input files and to run IFSM to estimate water consumption. The cow-calf phase is based on grazing extensive winter/spring rangeland and irrigated spring/summer pasture. We model this in the counterfactual using TomKat's soil/veg parameters but adding up to 6 inches of irrigated per month (for

	cow-calf stage only). Sources for water will be based on information found in the literature, except when primary data are available. This is consistent with the approach we intend to use for quantifying water consumption for in our own production system.
Water quality	As for water consumption, we propose to use Stackhouse-Lawson et al.'s IFSM input files to estimate nitrogen and phosphorus discharges to water. Values for selected heavy metals and toxins emitted to water as a result of feed production will be identified through secondary research. This is consistent with the approach we intend to use for quantifying water pollution for our own production system. Erdoded soil, bacteria from fecal matter and antibiotic and hormone residues in water courses are all additional impacts of conventional ranches which we are aware of; however, at the present time there are not enough data for us to quantify these aspects of water quality.
Soil	Our soil health will be compared to the soil health of the conventional beef cattle ranches. We will translate the difference between the two into measures of increased and sustained economic productivity. Our methodology for valuing improvements in soil health seeks to estimate the long-term *societal* value of this improved economic productivity.
Animal welfare	To capture the societal value of improved animal welfare delivered by our approach, we will rely on existing economic research on consumer and public preferences for improved animal welfare as a result of grass-finishing relative to conventional feedlot finishing. As a result we will not need to establish a standalone value for 'animal welfare' for the counterfactual; we will just need to confirm that the counterfactual is sufficiently similar to the conventional ranching scenario described in the underlying research.
Nutrition	Similar to animal welfare, our approach to valuing nutrition will address the differential impact on health of consuming grass-finished beef versus grain-finished beef. We therefore do not need to establish a standalone value for 'nutrition' for the counterfactual.

4. Projected impacts of intensive rotational grazing

4.1. Summary

4.1.1. *Key question addressed*

What are the potential environmental outcomes of intensive rotational grazing at TomKat Ranch[22]?

Specifically, this section provides recommendations on how to estimate the likely change between TomKat Today and TomKat Tomorrow in terms of:

1. Soil and sward characteristics, namely water holding capacity, organic carbon content, bulk density, run-off, bare ground, and perennial grass cover;
2. Overall net soil carbon sequestration;
3. Forage productivity;
4. Excess nutrients; and
5. Biodiversity.

4.1.2. *Summary of our approach*

Predicting environmental outcomes of intensive rotational grazing is complex, due to limitations and uncertainties in the underlying science, as well as the highly context- and management practice-dependent nature of results. Our approach for identifying reasonable assumptions for TomKat Tomorrow was to:

- Conduct an initial scan of peer-reviewed literature to identify the range of potential outcomes of intensive rotational grazing relevant to the analysis (section 4.2.2); and
- Make recommendations specific to TomKat using a combination of primary and secondary data sources. These sources, in order of preference, are:
  1. Primary data collected at TomKat Ranch evidencing current conditions and potential outcomes of intensive rotational grazing. However, these data are limited due to the fact TomKat has only been practicing intensive rotational grazing for three years and has only conducted one year of soil sampling;
  2. Model results e.g. the Integrated Farm System Model (IFSM) predicts how changes in soil and vegetation variables (e.g. organic carbon content) lead to changes in outputs (e.g. forage productivity) and environmental outcomes (e.g. water quality);
  3. Results from other studies or meta-analyses that we believe can be reasonably extrapolated to TomKat Ranch; and,
  4. Professional judgement informed by 1-3 above (e.g. where the literature or primary data suggest a range of possible outcomes).
- Additionally we hope that external expert peer-review of this Section will contribute to 2-4 above.

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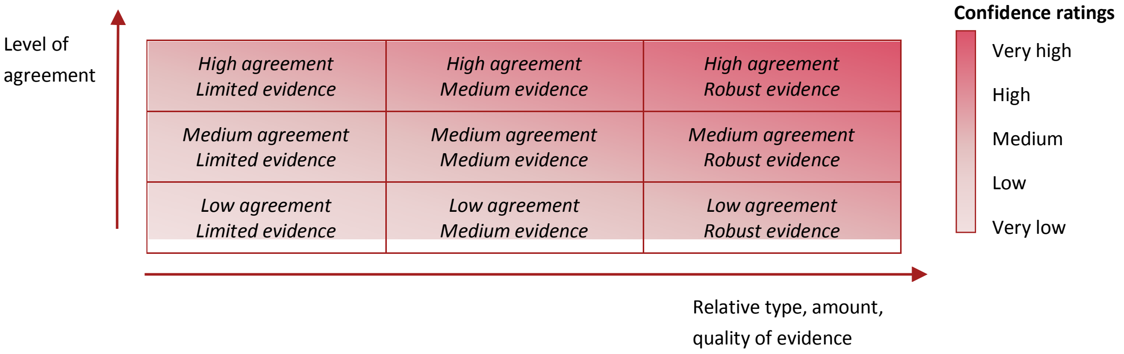
[22] We may, from time to time, lease land in the local area beyond TomKat Ranch to graze cattle. However, we focus our analysis on TomKat Ranch only as this is our primary and permanent grazing area.

4.1.3. ***Dealing with uncertainty***

We use a qualitative confidence rating to communicate the level of uncertainty surrounding specific recommendations within this Section. We follow the approach used by the Intergovernmental Panel on Climate Change (Mastrandrea, et al., 2010), which defines confidence as a qualitative judgement based on two scales: (1) relative ‘type, amount, quality and consistency’ of evidence; and (2) the degree of agreement. There are five levels of confidence: “very low,” “low,” “medium,” “high,” and “very high”. The relationship between these levels and the two judgement scales are described in the graphic below. Confidence is not a measure of statistical or probabilistic likelihood.

Confidence ratings, as determined by level of evidence and agreement



High agreement *Limited evidence*	*High agreement* *Medium evidence*	*High agreement* *Robust evidence*
Medium agreement *Limited evidence*	*Medium agreement* *Medium evidence*	*Medium agreement* *Robust evidence*
Low agreement *Limited evidence*	*Low agreement* *Medium evidence*	*Low agreement* *Robust evidence*

Source: IPCC (2010)

4.1.4. ***Summary recommendations***

Recommendations for each of the five outcome categories of identified in Section 4.1.1 are summarized below. Given the limitations and uncertainties surrounding these outcomes, as a general recommendation, we suggest primary measurements to validate or adjust these assumptions over time.

4.1.4.1. Soil and sward characteristics

Table 6 summarizes the recommended TomKat Tomorrow assumptions for soil and sward characteristics, as well as the confidence ratings we have ascribed to these assumptions, and references to subsequent sections where their derivation is described in more detail.

Table 6: Soil and sward characteristics

Characteristic	TomKat Today status	Proposed TomKat Tomorrow status	Basis for TomKat Tomorrow recommendation	Confidence rating	Section reference
Perennial grass cover	16%	40%	TomKat expert judgement of target perennial grass cover, which is informed by three years of primary data and some supporting evidence in the literature.	Medium	4.2.3.1
Water holding capacity	0.135 cm/cm	0.18 cm/cm	Good evidence in literature to suggest intensive rotational grazing improves water holding capacity. Recommended value based on maximum value of water holding capacity for TomKat soil types (NRCS, 2015).	High	4.2.3.2
Organic carbon content (0 to 10 cm)	3.42%	4.00%	TomKat expert judgement of target organic carbon content, supported by literature which suggests that intensive rotational grazing leads to increase in topsoil carbon. Similar rate of increase measured at another Californian ranch.	Medium	4.2.3.3
Dry bulk density	1.16 Mg/m^3	1.10 Mg/m^3	Increase in plant cover and animal hoof action lead to decrease in bulk density according to the literature. Recommended value based on current lower bound for TomKat soils.	Medium	4.2.3.4
Bare ground	15%	6%	Based on assumption that long-term bare ground can be limited to 2012 (pre-drought) proportions measured at TomKat Ranch.	High	4.2.3.5
Run-off curve number	79	74	Bare ground is expected to decrease, which implies lower runoff. Recommended value based on run-off data from NRCS (2015).	Medium	4.2.3.6
Whole profile drainage coefficient	0.518	0.6	Improved drainage expected due to reduced compaction in TomKat Tomorrow. Recommended value based on drainage data from NRCS (2015).	Medium	4.2.3.7
Nitrogen/nitrate content	[TBC - pending soil survey results]	Increase expected (not quantified)	Expect soil nitrogen to increase based on increase in soil carbon and plant cover. This will be modelled implicitly within IFSM.	Low	4.2.3.8

4.1.4.2. Soil carbon sequestration

For our grasslands, we recommend using an average soil carbon sequestration rate of 410 kgC/ha/year for the top 50cm of soil (Conant, et al., 2003) for 2015 to 2040. This rate represents the average increase in sequestration for intensive rotational grazing compared to continuous grazing found by Conant et al. across four different sites.

We recommend considering an alternative rate of carbon sequestration for sensitivity analysis i.e. 330 kgC/ha/year (Post & Kwon 2000).

We assume that 200 acres (80 hectares) of TomKat Ranch will be converted from coastal shrub to grassland. The literature suggests that this will result in a loss of 39 tC/ha from these soils (Silver et al., 2010). For further detail, see section 4.2.4.

Confidence rating: Medium.

4.1.4.3. Forage productivity

We recommend using IFSM with the assumptions for soil and sward changes listed in Table 6 to predict TomKat Tomorrow forage productivity. IFSM predicts that annual forage production would increase by 26% from 101 metric tons of dry matter to 127 metric tons. For further detail, see section 4.2.5.

Confidence rating: Medium.

4.1.4.4. Excess nutrients

We recommend using IFSM with the assumptions for soil and sward changes listed in Table 6 to predict level of excess nutrients for TomKat Tomorrow. IFSM predicts that the impacts of excess nutrients will increase by 19%. For further detail, see section 4.2.6.

Confidence rating: Low.

4.1.4.5. Timing of outcomes

We assess TomKat Tomorrow outcomes in 2040.

Available evidence suggests that different outcomes of intensive rotational grazing manifest over different time periods. More generally, the rate of environmental restoration depends on factors such as rainfall, temperature, and species presence, among others, and is therefore difficult to predict. The maximum time period of the intensive rotational grazing studies we reviewed is 25 years, and most studies were for fewer than 10 years. We therefore believe it is prudent to consider a timeline of no more than 25 years. The choice of 25 years (i.e. to 2040) is somewhat arbitrary, but we consider it to be a reasonable period to evaluate the full potential of intensive rotational grazing while hoping in practice that significant changes will be observed over a much shorter period.

We note that several studies suggest that changes would be expected to continue well beyond these timeframes. For example, in a meta-analysis of over 300 studies, Conant et al. (2001) found that changes in carbon sequestration rates are highest for the 40 years after a change in management practices but can continue for many years after that. Potter et al. (1999) found empirical evidence that degraded land can continue to sequester carbon for 98 years.

4.2. Evidence and recommendations

4.2.1. ***Overview of intensive rotational grazing***

Intensive rotational grazing is a livestock management system that aims to emulate natural grazing. Based on the observation that natural grasslands are sustained by the grazing and trampling action of large herds of roaming herbivores, intensive rotational grazing keeps livestock herds in small paddocks for short periods of time. Herds are quickly moved on to new paddocks, giving each area of land a prolonged period of rest and regrowth.

The Rangeland Monitoring Network uses the term Intensive Rotation (or Management Intensive Grazing) and defines this as 'a system with a minimum of 4 paddocks/pastures through which cattle are moved such that they remain on one pasture no more than 7 days and do not return to a pasture until it has not been grazed for a minimum of 21 days.' However, various other terminology and approaches to intensive rotational grazing exist (see Box 1).

Box 1: Intensive rotational grazing is variously referred to as:

- Rotational grazing
- Planned grazing
- Management-intensive grazing (MiG)
- Multi-paddock grazing
- (Intensive) short-duration grazing (SDG)
- High intensity - low frequency
- Cell grazing
- The Savory Grazing System
- Time-controlled grazing
- Non-selective grazing
- Planned conservation grazing

While each term may indicate slightly different management practices, we have treated them as sufficiently similar to inform our research into the potential outcomes associated with intensive rotational grazing.

Supposed benefits of intensive rotational grazing over the traditional practice of continuous grazing include environmental benefits, such as plant diversity and soil carbon sequestration (Teague, et al., 2011), animal welfare benefits, such as a healthier diet for cattle (Undersander, et al., 2002), and financial benefits, as a result of high stocking densities and limited inputs (Savory & Parsons, 1980).

While some support for the benefits of intensive rotational grazing can be found in the scientific literature, there is a far larger body of anecdotal evidence, with farmers and ranchers from across the world attesting to the benefits that the method has delivered for them (Holistic Management International, 2015; Soils For Life, 2012; Savory Institute, 2013).

However, not all agree that intensive rotational grazing is beneficial. For example, Briske et al (2008) reviewed a number of studies concerning rotational grazing on rangelands which looked for effects on plant production (19 studies) and animal production (28 studies). They found that "the experimental evidence indicates that rotational grazing is a viable grazing strategy on rangelands, but the perception that it is superior to continuous grazing is not supported by the vast majority of experimental investigations". This study and its conclusions have been subject of debate (e.g. Teague et al. 2013; Wolf & Horney forthcoming), and we do not consider it to be the final word on the subject (see section 4.2.5).

The lack of academic consensus may be due to:

- Potentially inconsistent application of "intensive rotational grazing" – a number of terms are used to refer to similar management systems, and as these are not consistently defined it is unlikely they are consistently applied (Teague, et al., 2013).
- A lack of accurate grazing management information (time of year, duration of individual paddock use, intensity of animals (number/herd size) class of livestock) included in the grazing studies.

- A lack of good data – the scale of the system being measured means that experiments should ideally measure large areas of land over long time periods. Practical constraints mean that existing studies tend to have small sample sizes and short durations, making it difficult to reach firm conclusions (Teague, et al., 2013).
- Difficulty in doing 'scientific' experiments – the nature of intensive rotational grazing is that it relies on human judgements, particularly as to when livestock should be moved, according to condition of the animals, plants and weather. This subjectivity makes it difficult to conduct consistent scientific tests of the method (Teague, et al., 2013).
- On average the differences between grazing strategies may be minimal and/ might be overwhelmed by site-specific conditions, especially over short time periods.

Implications of this for our recommendations are:

- There is evidence that intensive rotational grazing can result in environmental and financial benefits if the methods are applied appropriately. However, achieving these benefits through intensive rotational grazing may also be contingent on other as yet unspecified factors. Early evidence of improvements suggests that we can realize at least some of the purported benefits. This is what we seek to credibly represent in the TomKat Tomorrow scenario.
- However, estimating the status of soil and sward characteristics in the TomKat Tomorrow scenario is complex due to limited consensus in the literature. Therefore, in addition to the literature, where possible we take into consideration primary data, and predictions of models that provide a reasonable representation of our production system. Furthermore, where we extrapolate results from peer-reviewed studies we ensure that the study context is sufficiently similar to our production system.
- While our recommendations in this section are made based on the best available information, they are inherently uncertain. To reflect this, we have assigned confidence ratings to each recommendation, as described in section 4.1.2 and these confidence ratings will be used to inform sensitivity analyses on our final results.

4.2.2. *Overview of potential outcomes of intensive rotational grazing*

Our first step to making recommendations for TomKat Tomorrow was to identify the potential changes resulting from intensive rotational grazing. To do this, we conducted a literature review of published studies that examined the impacts of intensive rotational grazing compared to continuous grazing. We reviewed 25 studies, including two meta-analyses covering 59 studies between them (see Appendix A2). We identified the following impacts that could affect the results of our analysis and discuss in turn how they might apply to us in Sections 4.2.3 to 4.2.7:

- Perennial grass cover (Section 4.2.3.1)
- Water holding capacity (4.2.3.2)
- Organic carbon content (4.2.3.3)
- Bulk density (4.2.3.4)
- Bare ground (4.2.3.5)
- Run-off/erosion (4.2.3.6)
- Soil drainage (4.2.3.7)
- Soil nitrogen/nitrate/ammonium (4.2.3.8)
- Soil carbon sequestration (4.2.4)
- Forage production (4.2.5)
- Excess nutrients (4.2.6)
- Biodiversity (4.2.7).

4.2.3. ***Soil and sward characteristics***

N.B. 'Sward' refers to the top layer of the soil and the vegetation growing on it.

4.2.3.1. Perennial grass and other vegetation cover

Recommendation: We hypothesize that with intensive rotational grazing, perennial grass coverage can be increased from 16% in TomKat Today to 40% in TomKat Tomorrow. Our hypothesis is based on the natural history of California grasslands (Barry, et al., 2006; Menke, 1992) and supported by recent measurements of perennial grass cover at TomKat Ranch (Henneman et al. 2014).

Confidence rating: Medium. Our early measurements show a positive trend in native perennial grass cover under our grazing system; 40% perennial grass cover has been recently been recorded in parts of California, and is consistent with the historic composition of local natural grasslands (University of California, 2015). However, the literature on the impact of intensive rotational grazing on perennial grass cover has low agreement.

4.2.3.1.1. Rationale

Historically, California's grasslands were dominated by native perennial grasses (Menke, 1992) and were grazed for millions of years by now-extinct megafauna (Barry et al, 2006). Invasive non-native grasses and forbs began to spread with the arrival of European settlers in the 18th and 19th century. Now only 1% of standing grassland crops are native to the state (Barry et al, 2006). While some argue that restoring native grasslands might reduce grazing productivity (Kimball & Schiffman, 2003), we believe that an increase in native perennial grass cover will have net ecosystem benefits.

Conservation of perennial grasses is one of our main environmental objectives at TomKat Ranch. In 2012, perennial grasses represented 8% of the land cover at TomKat Ranch (Henneman et al, 2014). The figure increased to 13% in 2013 and 16% in 2014. In Figure 3, we have extrapolated this short trend forward. Figure 3 suggests a near-maximum perennial grass cover of about 62% in 2050, and cover of about 58% by 2040 (date for TomKat Tomorrow). However, our target is only 40% perennial grass cover. This is based on:

1) Our knowledge of perennial grass cover recorded in the local area. For example, a survey of a regional park in Monterey found 39.1% perennial grass cover (Denise Duffy & Associates, Inc, 2012). Similarly, White (1967) found that native perennial bunchgrass (*stipa pulchra*) comprised up to 37% of aboveground standing crop. Stackhouse-Lawson et al (2012) assume perennial grass cover of 60% for cattle pastures in Shasta and Tehama counties;
2) The optimal ratio of perennial to annual grasses at TomKat for productivity purposes; and,
3) Acknowledgement that the trend in Figure 3 is only based on three years of primary data, and we do not know how it will proceed into the future. We will continue to monitor our perennial grass cover and compare it to this predicted increase. In the interim, we propose a target coverage of 40% which we consider to be ambitious but achievable.

Figure 3: Extrapolating primary data on perennial grass cover at TomKat Ranch

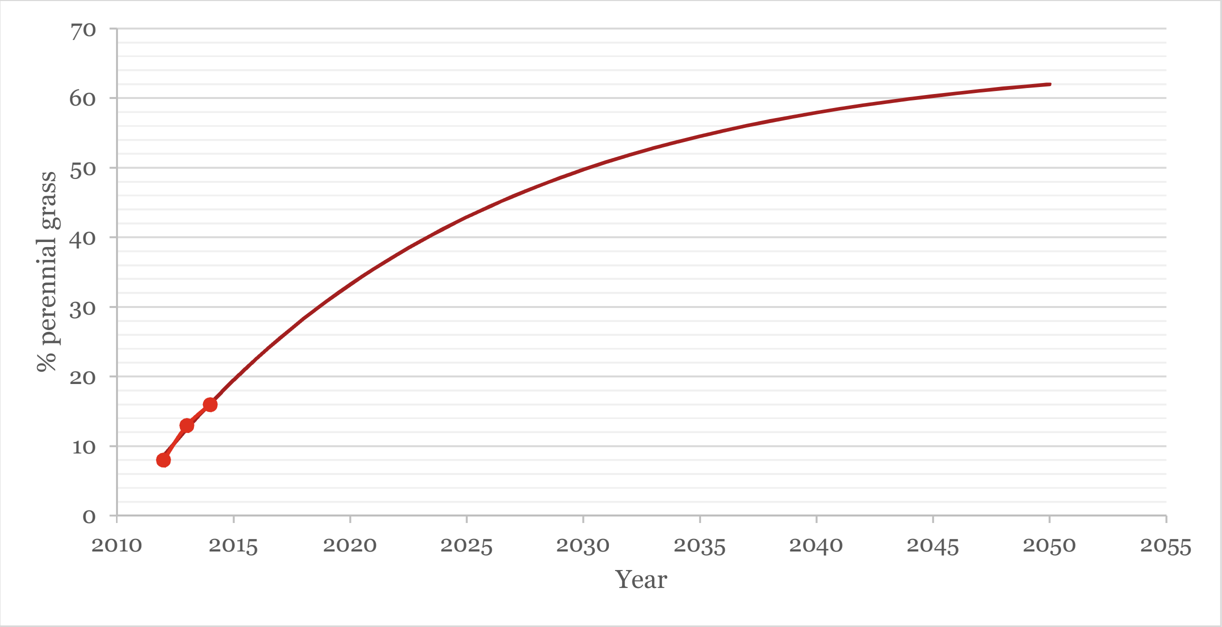


Table 7 shows how the relative proportions of vegetation at TomKat *could* change in order for perennial grasses to reach 40% cover. Hayes & Holl (2003) showed that forb cover increased under grazing in a coastal Californian prairie setting. We believe that forb cover at TomKat can also increase over time, with a target cover of 10%. Other options are possible (e.g. conversion of a larger percentage of coyote brush), but there is little evidence in the literature to suggest one option as more likely than another.

Table 7: Potential change in vegetation composition at TomKat Ranch[23]

	TomKat Today	TomKat Tomorrow
Perennial grasses	16%	40%
Annual grasses	22%	20%
Forbs	7%	10%
Dry thatch	4%	3%
Coastal shrubs (e.g. coyote brush)	20%	15%

Additional information considered: Table 8 summarizes the secondary research we found on the effect of intensive rotational grazing on vegetation. Several studies found no clear relationship between perennial grass cover and intensive rotational grazing (Biondini & Manske, 1996; Manley & al, 1997; Martin & Severson, 1988; Hall, et al., 2014), although some did find such a relationship (Earl & Jones, 1996; Henneman, et al., 2014; Teague, et al., 2004). A meta-analysis of the effect of grazing on plant composition in California grasslands found “native grass cover generally increased with grazing, although the high variation among studies was not predicted by the explanatory variables we evaluated” (Stahlheber & D'Antonio, 2013).

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[23] Excludes bare ground, weeds and trees, so percentages do not add up to 100%.

To summarize, findings in the literature are variable but current and historical evidence suggests that 40% perennial grass cover is a realistic target. We therefore have medium confidence in our hypothesis for perennial grass cover.

Table 8: Evidence of relationship between intensive rotational grazing and vegetation

	Reference	Findings
🟢	Earl & Jones 1996	Palatable grasses increased in multi-paddock grazing
🟢	Heitschmidt et al 1987b	Crude protein and organic matter digestibility higher with rotational grazing
🟢	Henneman et al 2014	Perennial grasses increased over time with intensive rotational grazing (at TomKat Ranch)
🟢	Stahlheber & D'Antonio 2013	Native grass cover generally increased with grazing, although with high variation among studies (meta-analysis - rotational grazing not studied)
🟢	Teague et al 2011	Desirable high seral grasses dominant in multi-paddock grazing
🟢	Teague et al 2004	Rotational grazing had greater increases in perennial basal area when weather is favorable, smaller decreases in drought conditions
⚪	Bartolome 2004	Grazing removal increased perennial grass abundance (rotational grazing not studied)
⚪	Biondini & Manske 1996	No differences found in species composition between rotational and season-long grazing
⚪	Hall et al 2014	No consistent differences in plant species composition between grazing methods
⚪	Manley et al 1997	Effects of grazing strategy on vegetation were insignificant
⚪	Martin & Severson 1988	Perennial grass density with the Santa Rita grazing system was not different from continuous grazing

4.2.3.2. *Water holding capacity*

Recommendation: We hypothesize that with intensive rotational grazing water holding capacity can be increased by 33%, from 0.135 cm/cm in TomKat Today to 0.18 cm/cm in TomKat Tomorrow.

Confidence rating: High. The scientific literature suggests with good agreement that water holding capacity improves as a result of intensive rotational grazing, so we are confident that water holding capacity at TomKat will increase. However, there is less evidence to inform by how much it will increase, which precludes a 'very high' confidence rating.

4.2.3.2.1. Rationale

Our recommendation is based on the assumption that water holding capacity will increase with intensive rotational grazing (see Table 9 for predominately supporting evidence). Based on a substantial review of the available literature where no quantified relationships pre and post intensive rotational grazing where reported, we assume TomKat Tomorrow water holding capacity is based on the maximum value in TomKat's current soil profile. The NRCS Web Soil Survey disaggregates TomKat's soil profile into 20 sub-types soil (including Botella clay loam, Cayucos clay, Gazos loam, Santa Lucia loam etc.) and a total of 34 different combinations of sub-types of soil, slope and erosion. The calculations for water holding capacity are based on organic matter, soil texture, bulk density, and soil structure, with corrections for salinity and rock fragments. The maximum value of 0.18 cm/cm for water holding capacity relates to the soil characteristics of Botella clay loam.

We do not currently measure water holding capacity so it is not possible to infer from primary data. Additionally water infiltration rate is not a parameter within IFSM.

Additional information considered: An alternative approach to calculating water holding capacity is to generate a TomKat specific pedotransfer function using easier to measure soil characteristics. We concluded that generating and applying a pedotransfer function would be unlikely to provide improved predictions in TomKat's case for a number of reasons: 1) a pedotransfer function would be limited by the number of primary soil samples collected by TomKat; 2) the majority of functions are based on data generated outside of North America and do not represent the climatic conditions at TomKat Ranch; and, 3) the pedotransfer functions in the ROSETTA software, software developed by the USDA which provides several pedotransfer functions developed with neural network analysis (Schaap, et al., 2001), does not include soil organic matter—a key goal of intensive rotational grazing and a driver of water holding capacity.

As summarized in Table 9, the majority of evidence suggests that water holding capacity increases as a result of intensive rotational grazing. Of the authors that conclude an increase, Mapfumo et al. (2000) is the only paper to present a quantifiable change in amount. However, these figures are not recommended for use in this analysis for two reasons: 1) the three grazing practices analyzed (heavy, medium and light) are continuous, and 2) outputs are not usable without significant assumptions (for example, measurement units are reported by volume, and not usable without a bulk density figure).

Table 9: Evidence of relationship between intensive rotational grazing and water holding capacity/storage

	Reference	Findings
●	Beukes & Cowling 2003	Grazing leads to increased stability, infiltration, and a higher water content due to a more active soil biota
●	Teague et al 2013	Multi-paddock grazing increases perennial basal, represented by higher fungal to bacterial ratio which indicates superior water holding capacity and nutrient availability
●	Teague et al 2011	Water-holding capacity is higher with multi-paddock than light or heavy continuous, based on its positive relationship with soil C
●	Weber & Gokhale 2010	Volumetric water content is significantly higher for intensive rotational grazing than rest-rotation (low density for long periods of time)
●	Mapfumo et al 2000	Change in water holding capacity for medium and light grazing, was positive and significantly greater than that for the heavy grazing.

4.2.3.3. Organic carbon in topsoil

Recommendation: We hypothesize that with intensive rotational grazing organic carbon concentration in the topsoil (0-10 cm) can increase by 17% from 3.42% for TomKat Today to 4.00% for TomKat Tomorrow.

Confidence rating: Medium. While there is good evidence that carbon content in the topsoil will increase under intensive rotational grazing, there is less evidence to suggest by how much.

4.2.3.3.1. Rationale

Our hypothesis that organic carbon will increase is consistent with findings by Teague et al. (2011) that soil organic matter was significantly higher under intensive rotational grazing. The direction of change is also consistent with findings by Schuman, et al. (1999), Derner, et al., (1997), Henderson (2000), Manley, et al. (1995) and Povirk (1999) that soil carbon in the topsoil increases under grazing in general. An increase in organic carbon content in the topsoil is further consistent with our assumption of increased perennial grass cover (section 4.2.3.1). Perennial grass cover is positively correlated with soil carbon storage due to its higher root biomass and litter base (Mapfumo, et al., 2002).

To date, we have not consistently measured change in topsoil organic carbon over time at TomKat Ranch. Therefore, we cannot use primary data to estimate the value for TomKat Tomorrow. However, we believe an increase of 17% to 4.00% is possible. It represents an increase of less than one standard deviation from the mean topsoil carbon concentration for TomKat Today (3.42%), and is within the current range (2% to 5%)[24]. One grassfed beef ranch in San Benito County (Morris Grassfed) has recorded a 7.5% increase in organic carbon in the top 10cm over 4 years (between 2011 and 2015) from 3.07 to 3.30% (Soil Carbon Coalition, 2015). Based on the above, we propose that an increase of 17% over 25 years is reasonable.

In section 4.2.3.1, we hypothesize that in TomKat Tomorrow, coastal shrubs such as coyote brush will decrease from 20% to 15% cover. Zavaleta & Kettley (2006) found a positive relationship between coyote brush invasion and soil carbon, which implies a loss of soil carbon if coastal shrub is converted to grass. However, Zavaleta & Kettley's results were explained by root biomass increases between depths of 15 and 47cm, and therefore does not affect our assumptions for topsoil carbon concentration. Loss of carbon storage at lower depths is addressed in section 4.2.4, where we consider carbon storage in the top 1.0m of soil.

Additional information considered: As summarized in Table 10, evidence on the effect of intensive rotational grazing on organic carbon in the topsoil is somewhat mixed in the literature. While Teague et al. (2011) found that soil organic matter was significantly higher under intensive rotational grazing, Beukes & Cowling (2003) found the opposite. The latter authors suggest that their result may be due to the more active microbial community found under intensive rotational grazing, which could lead to faster turnover of organic matter.

When taking into account broader literature (e.g. beyond intensive rotational grazing to grazing in general or grassland management), the evidence to support an increase in organic carbon concentration at TomKat Ranch is stronger. For example, Lal (2002), Conant et al. (2001), Schuman, et al. (1999), Derner, et al., (1997), Henderson (2000), Manley, et al. (1995) and Povirk (1999) all find that improved grazing practices (in general) can increase carbon in the topsoil.

Table 10: Evidence of relationship between intensive rotational grazing and organic carbon in topsoil

	Reference	Findings
🟢	Teague at al 2011	Soil organic matter was significantly higher under multi-paddock grazing than heavy continuous or light continuous grazing.
🟢	Sanjari et al. 2008	Up to 626 kgC/ha/year more soil organic carbon in topsoil under time-controlled grazing compared to continuous grazing, but result not statistically significant ($p = 0.16$).
⚪	Manley et al. 1995	Found no significant differences in soil C in top 91cm of soil between continuous and rotationally deferred/short-duration grazing.
🔴	Beukes & Cowling 2003	High-intensity, low-frequency grazing significantly lowered the amount of organic carbon in the topsoil.

4.2.3.4. Bulk density

Recommendation: We hypothesize that with intensive rotational grazing, average dry bulk density at TomKat can be reduced by 16% from 1.16 Mg/m^3 in TomKat Today to 1.10 Mg/m^3 in TomKat Tomorrow.

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[24] Based on TomKat 2015 soil survey. Note that values of up to 10% organic carbon in the topsoil were recorded, but were considered outliers due to their proximity to riparian areas and therefore excluded from the analysis.

Confidence rating: Medium. There is some scientific evidence supporting the relationship between intensive rotational grazing and bulk density, and a medium level of agreement. However, there is less evidence on how much bulk density will change.

4.2.3.4.1. Rationale

Current dry bulk density at TomKat ranges between 0.88 and 1.47 Mg/m^3, with an average of 1.16 Mg/m^3. We believe that average bulk density will decrease in TomKat Tomorrow because:

- We believe bare ground will decrease (see section 4.2.3.5) and increasing vegetation cover tends to reduce soil bulk density (Pluhar et al. 1987); and
- Intensive rotational grazing can limit animals' impact on soils that are susceptible to compaction (Sanjari et al 2008, Teague et al 2011).

There is insufficient literature to suggest a quantitative relationship between bulk density improvement and vegetation cover increase or intensive rotational grazing. We believe it is reasonable to hypothesize that average bulk density of TomKat Tomorrow can decrease by 16% i.e. 1.10 Mg/m^3. This is still well within the current range of bulk density measurements.

Additional information considered: There evidence in the literature to suggest that intensive rotational grazing reduces bulk density / soil compaction e.g. Sanjari et al. (2008). However, Abdel-Magid et al. (1987) found no impact on bulk density from different grazing treatments.

Table 11: Evidence of relationship between intensive rotational grazing and bulk density

	Reference	Findings
●	Sanjari et al 2008	A significant increase in bulk density was found under continuous grazing but not under time-controlled grazing.
●	Teague et al 2011	Results showed bulk density was lower under multi-paddock grazing than heavy continuous or light continuous grazing, but not at a statistically significant level (p>0.05).
●	Abdel-Magid et al 1987	No significant differences in soil bulk densities between continuous grazing, rotationally deferred, and short duration grazing.

4.2.3.5. Bare ground

Recommendation: We hypothesize that with intensive rotational grazing, bare ground at TomKat Ranch can be reduced from 15% to 6% (2012 pre-drought proportion of bare ground measured at TomKat).

Confidence rating: High. While there is some disagreement in the literature on the relationship between intensive rotational grazing and bare ground, combining this with on-site monitoring at TomKat Ranch we are confident of our hypothesis that grazing can decrease bare ground to pre-drought levels.

4.2.3.5.1. Rationale

On-site monitoring at TomKat Ranch shows a decrease in bare ground from 6% to 3% between 2012 and 2013, but a significant increase of five-fold to 15% in 2014. It is believed this is due to the recent severe drought experienced in California. Given the considerable fluctuations, it is not possible to predict a long-term trend. We therefore recommend an assumption that, in the long-term, bare ground at TomKat can be limited to pre-drought proportions i.e. 6%.

Additional information considered: Research in the literature shows some evidence for a decrease in bare ground under intensive rotational grazing (Manley et al. 1997; Teague et al. 2011), although as with other soil parameters, there is also evidence to the contrary. Regardless, our preference is to apply an assumption based on primary data.

Table 12: Evidence of relationship between intensive rotational grazing and bare ground

	Reference	Findings
🟢	Manley et al 1997	Significantly more bare ground under season-long heavy grazing than for short duration grazing and rotationally deferred grazing in certain years.
🟢	Teague et al 2011	Bare ground was significantly higher under heavy continuous grazing than under multi-paddock grazing.
🔴	Pluhar et al 1987	Rotational grazing significantly increased bare ground and decreased vegetation cover compared to continuous grazing at moderate stocking rates.

4.2.3.6. Run-off/erosion

Recommendation: We hypothesize that with intensive rotational grazing, the run-off curve number at TomKat Ranch can be reduced from 79 to 74. This is based on the assumption that bare ground decreases from 15% to 6% in TomKat Tomorrow (2.3.5), which moves our soil from borderline 'fair' category of pasture quality to safely within the 'good' category as defined by the NRCS[25].

Confidence rating: Medium. While we have high confidence that bare ground at TomKat will decrease, which implies lower runoff, the evidence in the literature linking intensive rotational grazing and runoff has low agreement. Therefore our overall confidence rating is medium.

4.2.3.6.1. Rationale

The runoff curve number is used to predict direct runoff from a rainfall event, which in turn affects the amount of erosion sediment loss. Therefore, the impact of reducing the runoff curve number for TomKat Tomorrow is that runoff and sediment loss (and associated phosphorus and carbon loss through erosion) should decrease. Sediment loss reduction is consistent with our predictions that organic carbon in the soil will increase and bare ground will decrease in TomKat Tomorrow (sections 4.2.3.3 and 4.2.3.5), since these factors are linked to reduced erosion (Miller & Donahue, 1990).

Additional information considered: Evidence in the literature for the impact of intensive rotational grazing on runoff and sediment loss is mixed, as can be seen in Table 13. It is worth noting that two of the studies identified (Beukes & Cowling 2003, Warren et al. 1996) compared intensive rotational grazing with no grazing, so it may be the case that continuous grazing would have had the same or potentially more detrimental impacts on runoff and erosion.

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[25] The NRCS defines 'fair' pasture as '50 to 75% ground cover and not heavily grazed' and 'good' pasture as '>75% ground cover and lightly or only occasionally grazed' (USDA, 1986). Reducing bare ground and dry thatch to 6% and 3%, respectively, increases ground cover at TomKat Ranch from approximately 78% (which we consider prudent to categorize as 'fair' quality) to 91% (safely within the 'good' category). Our soil is predominantly hydrological group C (or C/D). Therefore moving from 'fair' to 'good' results in a change in runoff curve number from 79 to 74.

Table 13: Evidence of relationship between intensive rotational grazing and runoff, infiltration or erosion

	Reference	Findings
🟢	Rotz et al 2009	Converting cropland to perennial grassland through rotational grazing reduces erosion by 24% (as predicted by IFSM)
⚪	Beukes & Cowling 2003	Soil subject to high-intensity, low-frequency grazing had improved water infiltration capacity compared to un-grazed soil when rain was simulated on disturbed soils. However, no significant difference in infiltration when rain was simulated on sealed soils (which is closer to field conditions most of the time). No significant difference in erodibility found for disturbed or sealed soils.
🔴	Warren et al 1996	Short-duration grazing at progressively increased stocking rates progressively decreased infiltration and increased erosion compared to no grazing.
🔴	Pluhar et al 1987	Infiltration rates were lowest and sediment production was highest under rotational grazing compared to moderate continuous grazing.

4.2.3.7. Soil drainage

Recommendation: We hypothesize that with intensive rotational grazing, whole profile drainage coefficient at TomKat Ranch will increase from 0.518 for TomKat Today to 0.6 for TomKat Tomorrow.

Confidence rating: Medium. Our hypothesis for change in soil drainage is consistent with our hypothesis for change in water holding capacity, in which we have high confidence. However, there has been limited research into the specific relationship between intensive rotational grazing and soil drainage, so our overall confidence rating is medium.

4.2.3.7.1. Rationale

Our hypothesis is on the basis of: (1) the assumption that perennial grass cover will dominate vegetation in TomKat Tomorrow (see section 4.2.3.1); and (2) primary measurements at TomKat Ranch show that perennial grass had much higher hydraulic conductivity - and therefore better drainage (NRCS, 2010) - than that measured for annual grass (O'Geen et al, 2013). While we do not know exactly how the increase in perennial grass cover might alter specifically the whole profile drainage coefficient, increasing the value to 0.6 represents an assumption that all TomKat Tomorrow soil can be considered 'well drained' (currently 65%[26]).

This is consistent with the assumption made in section 4.2.3.2, where we applied the water holding capacity value for Botella clay loam (sloping, eroded) to the whole Ranch for TomKat Tomorrow. Botella clay loam (sloping, eroded) is considered 'well drained'.

Additional information considered: In terms of secondary research, we identified only one intensive rotational grazing study that specifically measured hydraulic conductivity. Teague et al (2011) found higher hydraulic conductivity under intensive rotational grazing, but the result was not statistically significant. The dearth of relevant studies means we cannot reasonably extrapolate results from the literature.

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[26] 65.1% of our grassland is currently considered to be 'well drained' according to NRCS Soil Survey. 'Well drained' is associated with whole profile drainage coefficient of 0.6 (Iglesias, 2006).

Table 14: Evidence of relationship between intensive rotational grazing and soil drainage

	Reference	Findings
🟢	Teague et al 2011	Hydraulic conductivity was higher under multi-paddock grazing than either heavy continuous or light continuous grazing, but not a statistically significant level.

4.2.3.8. Soil nitrogen, nitrate, and ammonium

Recommendation: We hypothesize intensive rotational grazing will lead to an increase in soil nitrogen, which would be consistent with the expected increase in biomass production, water holding capacity, and carbon content. We do not have primary soil nitrogen measurements over time to quantify the change, but it will be modelled by IFSM in estimating forage production and water quality.

Confidence rating: Low. While our hypothesis for an increase in soil nitrogen is consistent with our other hypothesized changes, the literature on the effects of planned and continuous grazing on nitrogen levels is limited and mixed.

4.2.3.8.1. Rationale

Soil nitrogen availability is a determinant of vegetation growth. Scientific research shows that nitrogen availability in the soil is affected by many chemical, physical, and climatic factors. Research suggests that nitrogen mineralization increases with soil water (De Neve & Hofman, 2002) as well as soil organic matter content (Geisseler & Horwath, 2013) and soil carbon (Conant et al., 2003). In TomKat Tomorrow, soil water, organic matter, and carbon are expected to increase due to intensive rotational grazing (see sections 4.2.3.2 and 4.2.3.3). Therefore, we hypothesize that soil nitrogen availability will also increase.

We do not have primary measurements of soil nitrogen over time to quantify the increase. Instead, we will assess its impact on TomKat Ranch through use of IFSM. IFSM uses relationships grounded in science from DayCent and Nitrogen Loss and Environmental Assessment Package (NLEAP) models to estimate nitrogen transformation (fixation, mineralization, nitrification, denitrification, volatilization, immobilization, leaching, and crop uptake) and movement between soil layers on a daily time step, which in turn informs its estimations of forage production and water quality. These functions take into account a broad range of inputs, including soil texture, water holding capacity, bulk density, precipitation, vegetation, manure application, and carbon dioxide flux. Therefore by using IFSM to model forage production and water quality (sections 4.2.5 and 4.2.6), we implicitly take into account potential changes in soil nitrogen.

Additional information considered: A review of the literature produced varied results. Biondini and Manske (1996) compared soil N mineralization and immobilization under rotational grazing, continuous grazing and no grazing. They found that net N mineralization on rotationally grazed land increased from 1.56 g/m^2 in 1987 to 7.25 g/m^2 in 1989 (460% increase over two years), whereas there was no clear trend for the other two treatments (which averaged net mineralization of 2.4 g/m^2). Conversely, Sanjari et al (2008) found a sharp, significant decrease in soil nitrate under intensive rotational grazing and in un-grazed areas, whereas nitrate increased significantly in one of the two continuously grazed areas. It is likely that N mineralization interacts significantly with other variables, such as weather and soil condition, so it is not simple to isolate the influence of grazing practices.

In the same study, Sanjari et al found increases in total organic nitrogen under intensive rotational grazing when soil physical properties were favorable, which was explained by an increase in soil ammonium. When soil was shallow and steep, no change in total nitrogen was found. Wilms et al (1990) found that short duration grazing reduced soil organic matter and nitrogen compared to un-grazed land.

In summary, the literature on the effects of intensive rotational grazing on nitrogen levels is mixed and limited.

Table 15: Evidence of relationship between intensive rotational grazing and soil nitrogen

	Reference	Findings
🟢	Biondini & Manske 1996	Net N mineralization increased by 460% under rotational grazing over two years, and did not show a clear trend with continuous grazing or no grazing.
⚪	Manley et al. 1995	Higher soil N in surface 30cm of grazed pasture compared to un-grazed. However, found no significant differences in soil N between continuous and rotationally deferred/short-duration grazing.
🔴	Sanjari et al 2008	Sharp decrease in nitrate levels at rotationally grazed site, where nitrate levels increased at one of two continuously grazed sites.
🔴	Wilms et al 1990	Short duration grazing reduced soil organic nitrogen compared to ungrazed land

4.2.4. ***Soil carbon sequestration***

Recommendation: We hypothesize that with intensive rotational grazing, we can achieve a sequestration rate of 410 kgC/ha/year for TomKat Ranch grasslands in the top 50 cm of soil. This implies that storage in the top 1.0m of soil for TomKat Ranch grasslands will increase by 8% from 207 tC/ha to 225 tC/ha by 2040.

Our recommendations for soil carbon sequestration are based on the most relevant values identified from the literature. We rely on the literature because:

We have not measured change in soil carbon pools over time at TomKat Ranch, so we cannot use primary data; and,

We considered using three models to estimate sequestration, but these were deemed not to be appropriate.

Confidence rating: Medium. There is good evidence to suggest that improved grazing practices can lead to soil carbon sequestration and our recommended sequestration rate for grasslands overall is consistent with our hypothesized increase in topsoil carbon. However, there are limited studies which report experimental data on changes in carbon storage due to intensive rotational grazing. It is worth noting that, quantifying carbon storage to a fixed depth rather than an equivalent soil mass potentially underestimates carbon storage in TomKat Tomorrow because bulk density is expected to decrease (section 4.2.4.1.2).

4.2.4.1. Rationale

Research shows there is significant potential to sequester carbon in temperate grasslands, but measured and modelled rates of carbon sequestration range from zero to more than 8,000 kgC/ha/year (Jones & Donnelly 2004). Carbon sequestration potential of grasslands depends heavily on the previous use and condition of the land. Soil carbon pools also vary widely: Silver, et al., (2010) found carbon storage in Californian rangelands differed by up to 173 metric tonnes of carbon per hectare (tC/ha) for the top 1.0 m of soil. Variability can be explained by soil type, clay content, climate, above-ground primary production, and land use. Therefore, our review took careful consideration of study contexts to identify the literature most relevant to TomKat ranch.

For TomKat Ranch, we identified studies that examine the additional carbon sequestration resulting from intensive rotational grazing compared to what the land would otherwise be used for in the counterfactual i.e. continuous grazing. We identified two published studies (Table 16). Of the two studies, Conant et al.’s (2003) value of 410 kgC/ha/year is more applicable to us because: (1) it is based on cattle grazing whereas Sanjari et al. (2008) look at the impacts of sheep; and (2) it incorporates a longer time horizon i.e. 25 years versus 6 years in Sanjari et al.’s study. The recommended value is similar to the average rate of 350 kgC/ha/year associated with 'improved grazing' generally, which was found by Conant, et al. (2001) in a meta-analysis of over 115 studies.

Table 16: Soil carbon sequestration – benefits of intensive rotational grazing over continuous grazing

Study	Description	CO2e sequestration rate of PG over CG (kg C / ha / year)	Comment
Conant et al (2003)	Measured soil carbon from 0 to 50cm in four pairs of fields, one of each pair had been used for intensive rotational grazing (for 3, 5, 21 & 25 years). The other field in each pair was extensively grazed (3 out of 4) or hayed (1 out of 4).	410 (average over four sites in Virginia, USA which were monitored over 3, 5, 21, and 25 years)	Similar situation to us with good time series.
Sanjari et al (2008)	Compared sheep grazing continuously and with time-controlled grazing over 6 years in Queensland, Australia. Carbon was measured in the top 10cm of soil	233	Unknown how similar sheep and cattle impacts are.

Current total carbon storage in TomKat Ranch grassland is approximately 207 tC/ha to 1.0 m depth[27], so applying our recommended assumptions implies carbon storage increases to 225 tC/ha by TomKat Tomorrow. This estimate is very similar to that calculated using the hypothesized TomKat Tomorrow values for topsoil carbon (section 2.3.3), bulk density (section 2.3.4), and the relationship identified by Silver et al (2010) between carbon storage and soil depth for Californian rangelands[28].

Silver et al. (2010) analyzed carbon storage in 48 profiles from Californian grasslands and found a range of 47 - 246 tC/ha for the top 1.0m of soil. The value predicted for TomKat Tomorrow is in the higher-end of this range, which is consistent with our expert judgement that the soils at TomKat Ranch are (and will continue to be) less degraded than average Californian grassland. The predicted rate of change in soil carbon storage to 1.0m over 25 years is 8%, which is lower than the change in

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[27] This value was calculated as follows:

1. We used TomKat primary data from 2015 on current organic carbon concentration (3.42%) and bulk density (1.16 g/cm^3) to calculate carbon storage in the top 10 cm of soil i.e. 39.7 tC/ha.
2. We then used the relationship between carbon storage and soil depth identified in Silver et al (2010) to estimate carbon storage to 1.0m depth. Silver et al (2010) found in a meta-analysis of carbon measurements from Californian grasslands that total soil carbon storage at one depth (*a)* can be predicted with confidence using measured carbon storage at another depth (*b*). This is done as follows:

$$CS_a = CS_b * y(a)/y(b)$$

where CS_a = carbon storage at soil depth a (in cm); and $y(a) = 2.79a^2 + 1725a + 13241$.

Applying the above method to TomKat, we estimate carbon storage for the top 1.0m as CS(100) = 39.7 * $y(100)/y(10)$ = 207 tC/ha. This estimate is very similar (only 2.1% difference) to average soil carbon measured at TomKat in 2013 (O'Geen et al., 2013).

[28] Based on carbon content of 4.00% and bulk density of 1.10, carbon storage in top 10cm of soil for TomKat Tomorrow is approximately 44 tC/ha. We can then estimate the carbon storage to 1.0 m depth as explained in footnote 6. This gives us an estimate of 230 tC/ha. This represents a difference of only 2.2% compared to the value predicted directly using the recommended rate of carbon sequestration of 410 kg/ha/year.

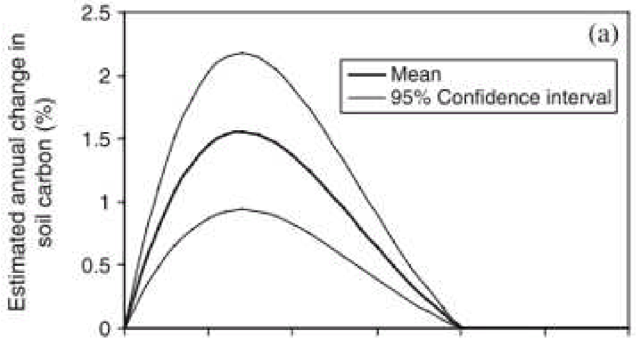
topsoil carbon predicted (17%). This is consistent with the literature, which suggests that topsoil is more active in sequestering carbon resulting from land use change (Jones & Donnelly, 2004).

Carbon sequestration is likely to continue beyond 2040. While we recognize that the sequestration rate will likely decline with longevity of grazing (Derner & Schuman, 2007), we also recognize that:

- Total soil carbon of 316 tC/ha was found at TomKat under certain patches of perennial grass (O'Geen et al., 2013). This implies that, on average, sequestration for TomKat grasslands at the recommended rate could continue for at least 155 years.
- In a meta-analysis of 115 studies, Conant et al. (2001) found that carbon sequestration rates are highest for 40 years after treatment begins. Further, Potter et al. (1999) found empirical evidence that degraded land can continue to sequester carbon for 98 years.

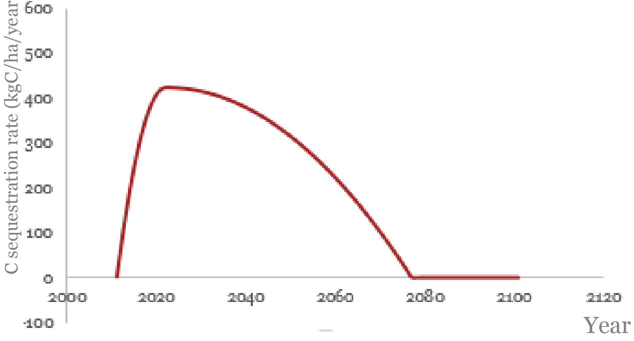
We assumed that the change in carbon sequestration rate followed a similar pattern to that identified by West & Six (2007) (see Figures 4a and 4b). This results in sequestration that averages 410 kgC/ha/year between 2015 and 2040, and declines slowly to 0 sequestration by 2078 (i.e. about 75 years after intensive rotational grazing started at TomKat Ranch).

Figure 4a: Change in annual soil carbon sequestration over time



Source: West & Six (2007)

Figure 4b: Rate of carbon sequestration assumed for TomKat Tomorrow: averages 410 kgC/ha/year from



Source: Own analysis

4.2.4.2. Coastal shrub

The assumed rate of sequestration of 410 kgC/ha/year for the top 50cm of soil does not apply to areas of coastal shrubs. For TomKat Tomorrow, we may choose to convert up to 200 acres (81 hectares) of coastal scrub to pasture. Silver et al (2010) found that woody plants, such as coyote brush, increase soil carbon in Californian grasslands by 39 tC/ha in the top 1.0m. We therefore assume that areas of TomKat Ranch which are converted from shrub to grass will result in a carbon pool loss of 39 tC/ha.

4.2.4.3. Compost application

We do not currently practice compost application, but would consider introducing this in future. Additional carbon sequestration benefits can occur with the addition of compost. The effects of compost application on soil carbon is relatively new field of research, however as the studies in Table 17 demonstrate, early evidence suggests composting has the potential to significantly increase soil carbon in grasslands.

Table 17: Carbon sequestration with compost application

Study	Description	CO2e sequestration rate (kg C/ha/year)	Comment
Ryals, et al., (2014)	Modelled application of compost (14 Mg C/ha) to degraded rangeland in California, soil carbon was measured over 10, 30, and 100 year time periods	10 years: Increased carbon sequestration of 130 – 158 gCO2e/m^2/year relative to control (no compost applied, moderately grazed) 30 years: Increased carbon sequestration of 63 – 84 gCO2e/m^2/year relative to control 100 years: No significant difference from control	Modelling-based using DAYCENT
Ryals & Silver (2012)	Single application of composted green waste to two rangelands (a valley grassland and a coastal grassland) to determine the effects on net primary productivity (NPP) and greenhouse gas emissions over three years.	Net ecosystem C storage increased by 25–70% without including the direct addition of compost C. Aboveground NPP at the valley site increased by 78% in the amended plots over the three years and 42% at the coastal site.	Study only covers three year period, but authors report 'no obvious sign of diminishing trend', implying that effects of compost application would likely be sustained over a longer period.
DeLonge, et al., (2013)	Modelled effects of composted manure and plant waste application on soil carbon in California grasslands over 3 years	2100	Purely modelling-based

4.2.4.4. Fixed depth versus equivalent soil mass

In this section, we quantify soil carbon to a specified depth using the relationship (IPCC, 2013):

Soil organic carbon (tC/ha) = depth (cm) x bulk density (Mg/m^3) x organic carbon concentration (%) x 10,000.

This 'fixed depth' or 'equal volume' method is recognized as good practice by the Intergovernmental Panel on Climate Change (IPCC) and widely deployed (Wendt & Hauser, 2013). However, this method can introduce errors when used to monitor soil carbon over a time during which soil bulk density also changes (Wendt & Hauser, 2013). In these cases, comparing carbon on an equivalent soil mass (ESM) basis (e.g. tonnes of carbon per 1,000 tonnes of soil mass) produces more reliable results (Ellert & Bethany, 1995).

We have decided to quantify according to fixed depth rather than ESM because:

(1) ESM requires bulk density (or soil mass) and organic carbon concentration measurements at two or more soil depths (Wendt & Hauser, 2013). We currently do not have these data for TomKat Ranch; and

(2) There are limited studies which employ ESM measurements from which to extrapolate (see section 4.2.4.5).

We acknowledge that, because bulk density at TomKat is expected to decrease, estimating carbon to a fixed depth potentially underestimates carbon storage for TomKat Tomorrow. We will test the impact of this through sensitivity analyses.

4.2.4.5. Additional information considered

We explored the following soil carbon models (Table 18) to estimate soil carbon sequestration. However, we believe that these are not appropriate for our analysis because they are either too simplistic and cannot represent intensive rotational grazing, or because they are too complex and require a level of data input which is not available currently.

Table 18: Soil carbon models

Model and developer	Description	Comment
CENTURY (Colorado State University)	Models biogeochemical processes to give estimates of soil carbon and other nutrients for systems including grassland and crops. Includes a number of management options, such as grazing and harvest effects.	Requires a prohibitive level of detail about the current system, e.g. plant nitrogen, phosphorus and sulfur content, detailed atmospheric inputs.
ROTHC26.C (Rothamsted Research)	A model of the turnover of organic carbon in soils on a years to centuries timescale that needs few inputs.	Doesn't use any information relating to grazing, other than bare ground.
COMET-Farm (NRCS & Colorado State University)	A simple model designed for use by farmers and ranchers to measure the GHG balance of their farms.	Doesn't allow for detailed grazing management strategy inputs.

We also considered using carbon sequestration rates from other literature. Post & Kwon (2000) conducted a review of literature reporting changes in soil with conversion of cropland and forests to (permanent) grassland. They include 39 values across 13 studies, which range from soil carbon *loss* of 900 kgC/ha/year (for conversion of subtropical moist forest to pasture) to soil carbon *increase* of 1,135 kgC/ha/year (for conversion of cropland in cool temperate steppe to perennial grass). Post & Kwon report a mean value across the studies of 332 kgC/ha/year. We ultimately decided that the rate reported by Conant et al. (2003) is more appropriate because:

- Soil carbon sequestration varies significantly depending on management practices and geographic contexts. We acknowledge the Conant et al. (2003) study differs in the latter to TomKat Ranch, but it does specifically consider the effect of intensive grazing, whereas Post & Kwon (2000) do not.
- The studies reviewed by Post & Kwon differ in terms of *both* management practices and geographic context: they consider the effects of converting cropland to pasture; they cover a range of ecosystems but none are coastal rangelands or areas with Mediterranean precipitation. We therefore believe it would be inappropriate to base our recommendation on these studies. The same rationale was applied to reject the 115 studies on soil carbon sequestration identified in the meta-analysis by Conant et al. (2001)[29].
- The recommended rate of 410 kgC/ha/year is comfortably within the range of values identified by Post & Kwon (2000) and Conant et al. (2001).
- We recognize there is considerable uncertainty around the rate of carbon sequestration. We recommend addressing this uncertainty in the sensitivity analysis by testing the impact of using a sequestration rate of 330 kgC/ha/year. We

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[29] We note that the average sequestration rate identified by Conant et al. (2001) for the conversion of cultivated land to pasture is 1,010 kgC/ha/year, which is more than three times higher than that identified by Post & Kwon (2000).

do not believe it is necessary to take into account the studies in Post & Kwon (2000) that report a soil carbon loss because they all relate to conversion of forests to pastures.

4.2.5. ***Forage productivity***

Recommendation: We recommend using IFSM to predict change in forage productivity for TomKat Tomorrow. We do this by reflecting the changes to soil and sward parameters as set out in section 4.2.3, in the model.

Confidence rating: Medium. We are confident based on early signs of land quality improvement at TomKat Ranch that forage production will increase through intensive rotational grazing. However, there is a significant quantity of research both supporting and refuting this hypothesis. Due to lack of sufficient primary data, we rely on modelling (IFSM) to estimate future change in forage production. IFSM is an industry-recognized model but, as with all models, has inherent limitations in simulating reality.

4.2.5.1. Rationale

We recommend using IFSM because:

- We have not previously measured forage production, so we are not able to draw on primary data;
- We prefer use of the IFSM model over use of secondary literature because the model takes into account the specific context and management decisions. It will be calibrated to our climate, geography, and herd size, for example;
- IFSM will be used to model greenhouse gases, water consumption and water quality (see Section 4.2). Therefore, using IFSM for estimating change in forage production will allow for consistency across the assessment; and,
- Use of a cattle industry-respected model appears more defensible than extrapolating from select studies, particularly given the mixed evidence in the literature.

IFSM predicts that, based on the change in soil and sward parameters in section 4.2.3, forage production will increase by 26% from 101 metric tons of dry matter in 2015 to 127 tons in 2040. We believe this prediction is reasonable in the context of anecdotal and academic research on intensive rotational grazing, and in line with our own expectations.

IFSM takes into account change in soil and vegetation characteristics to predict nitrogen availability. Initial testing of IFSM shows that nitrogen availability may be a limiting factor for forage productivity. Increase in nitrogen through fertilizer application or introduction of legumes in IFSM seems to lead to a significant increase in TomKat Tomorrow forage production. While we do not feel there is currently sufficient evidence to support an assumption of increased nitrogen levels of TomKat Tomorrow beyond the predictions of IFSM, we will conduct sensitivity analyses to understand this limitation further.

Additional information considered: We identified 67 studies that considered the effect of intensive rotational grazing on forage or livestock productivity, 59 of which are covered in meta-analyses by Sollenberger et al. (2007) and Briske et al. (2008). We looked at 12 of these which we considered to be of greatest relevance to us in more detail (Table 19).

The evidence is mixed, with the majority of studies finding no significant difference in forage production between the system most similar to intensive rotational grazing in the study, and continuous grazing. Sollenberger et al (2007) found that 85% of the 13 papers reviewed reported an advantage in forage quantity or carrying capacity for rotational grazing. However, Briske et al. (2008) reported that only 13% of 47 studies reviewed showed advantage of rotational grazing compared to continuous grazing in terms of production, and 25% of studies showed that continuous was superior to rotational (the remainder showed no difference between the two). Teague et al. (2013) argue that many of the studies included in Briske et al.'s meta-analysis did not practice 'adaptive management', which prevented them from achieving desirable soil, vegetation and livestock outcomes. Wolf & Horney (forthcoming) undertook a detailed review of the assumptions and operational definitions made by Briske et al. in their meta-analysis. They find that applying different (and they argue, equally valid) assumptions and definitions can lead to quite different conclusions to those made by Briske et al[30]. Furthermore, Wolf & Horney note that the majority of studies included in the Briske et al. meta-analysis had non-significant results, which limits their usefulness[9].

In summary, there is currently no consensus in the literature but this is an active area of research that will benefit from more transparent and robust evidence. While there is certainly evidence to suggest that intensive rotational grazing can lead to increased forage production, the level of disagreement has led us to seek an approach more tailored to our specific conditions i.e. an application of IFSM heavily customized with primary and secondary data inputs appropriate to TomKat ranch.

Table 19: Evidence of relationship between intensive rotational grazing and forage/livestock productivity

	Reference	Findings
🟢	Briske et al 2014	Greater plant production found in high precipitation areas with intensive rotational grazing
🟢	Hensler et al 2007	An additional 1645lb/ac of hay was harvested from MIG fields. Cows on MIG had greater weight gain and were able to graze for longer.
🟢	Sanjari et al 2008	Time controlled grazing had higher herbage production than continuous grazing
🟢	Sollenberger et al 2007	85% of reviewed papers reported an advantage in forage quantity or carrying capacity for rotational grazing
⚪	Biondini & Manske 1996	No significant differences in ANPP or animal production (mass gains) across treatments
⚪	Hall et al 2014	No significant differences found between the three stocking methods for herbage mass
⚪	Heitschmidt et al 1987a	No significant differences of ANPP between different stocking rates
⚪	Heitschmidt et al 1987b	Total standing crop greater with continuous grazing than planned, but quality is lower
⚪	Holechek et al 2000	Generally no difference in production if stocking rates are equal
⚪	Manley et al 1997	Grazing strategy had no effect on above-ground biomass
⚪	Martin & Severson 1988	Differences among pastures in herbage production are attributed mainly to climate and were not materially altered by grazing treatment
🔴	Briske et al 2008	Meta-analysis found an advantage of rotational grazing in forage quantity (compared to continuous grazing) in just 13% of studies

4.2.6. ***Excess nutrients***

Recommendation: We recommend using IFSM to predict change in excess nutrients (nitrogen and phosphorus loading) for TomKat Tomorrow.

Confidence rating: Low. There is limited research that specifically examines the effects of intensive rotational grazing on water pollution levels. Further, we do not have primary data to reference. While IFSM is an industry-recognized model, inherent limitations of simulation mean that overall our confidence in the predicted result for TomKat Tomorrow is low.

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[30] Based on interim findings from the authors.

4.2.6.1. Rationale

This recommendation follows the rationale outlined in section 4.2.4.

Based on the changes to soil and sward parameters in section 4.2.3, IFSM predicts that the impact of excess nutrients will increase by about 19%. This is due to the increase in area of grazeable pasture, which means a greater area of land receiving manure from cattle.

Additional information considered: In general, different grazing practices can have differing impacts on water quality, such as the quantity of nutrients and pathogens reaching waterways (Hubbard, et al., 2004). There is limited evidence that examines the effects of intensive rotational grazing specifically. Rotz et al (2009) found soluble phosphorus reduced by 23% over 4 years under intensive rotational grazing, and Sanjari et al (2008) found a reduction of extractable phosphorus of 77% over 5 years. Rotz et al (2009) used their model to estimate that soil nitrate leaching would increase under rotational grazing by 65%, but ammonia volatilization would reduce by 30%, compared to a previous crop-based land use.

Given the dearth of research in this area, we recommend using IFSM to predict the effects of soil and vegetation changes on water quality for TomKat Tomorrow.

Table 20: Evidence of relationship between intensive rotational grazing and water pollution

	Reference	Findings
●	Sanjari et al 2008	Extractable phosphorus fell more significantly under rotational grazing than continuous grazing, which could be explained by increase in plant phosphorus uptake.
●	Rotz et al 2009	Soluble phosphorus runoff reduced by 23% but nitrate leaching loss increased by 65% during transition of cropland to perennial grasses with rotational grazing, as predicted by IFSM

4.2.7. ***Biodiversity***

There is no one measure to monitor or evaluate biodiversity. Furthermore, there has been limited study of the impacts of intensive rotational grazing on any specific biodiversity measures. We therefore do not put forward any specific quantities to measure in relation to biodiversity, but provide a qualitative summary of relevant research.

Studies linking intensive rotational grazing and change in plant species were discussed in section 4.2.3.1. There is some evidence to suggest that intensive rotational grazing can lead to increase in more desirable plant species from a conservation and/or production viewpoint. Henneman et al. (2014) found that native perennial species cover increased significantly at TomKat Ranch within three years of intensive rotational grazing. There are anecdotal records from intensive rotational grazing ranchers of similar outcomes at farms in Vermont, New Mexico, and North Dakota (Stinner, et al., 1997). These ranchers also report increase in animal diversity on some occasions (e.g. increase in deer, earthworms, game birds and 'wildlife).

With regards to grazing more generally, Marty (2005) found grazing can help maintain native plant and aquatic biodiversity in vernal pools of California. Un-grazed pools had 47% relative lower cover of native species than continuously grazed pools. Germano, et al., (2012) found that populations of certain endangered small desert vertebrates in California increased significantly faster in grazed compared to un-grazed sites. However, they note that grazing has to be closely monitored to avoid having an adverse impact e.g. due to overgrazing in years of low rainfall. Conversely, in a study of the UK, Jofre & Reading (2012) found even 'conservation grazing' (i.e. grazing managed with a goal to enhance biodiversity) reduced the ability of habitats to support animal diversity, although it could improve plant diversity. Tallowin, et al. (2005) found that grazing at low stocking densities can enhance faunal biodiversity in species-rich grasslands but can also lead to an increase in harmful weeds.

The mixed literature implies that the impact of (planned) grazing on biodiversity depends on numerous factors, including the type of biodiversity (e.g. native vs. perennial, animal vs. plant) and geography of the site (ecosystem type, weather, soil types), as well as the natural (or baseline) levels of biodiversity at the site. Furthermore, different types of grazing suit different types of habitats.

5. Summary of primary and secondary data for modelling GHGs and water impacts

5.1. Summary

5.1.1. *Key question addressed*

What are the appropriate values for Integrated Farm System Model parameters where TomKat does not have primary measurements?

Section 2 explains the need to use models in order to quantify the environmental impacts of the beef production system. It also explains why the Integrated Farm System Model (IFSM) has been identified as the most appropriate model for the analysis.

IFSM offers a high degree of parameterization in terms of soil, vegetation and cattle, which allows it to capture subtleties in management practices as well as environmental conditions. However, TomKat does not currently have primary measurements for every parameter. While IFSM has numerous sets of default values, these may not be appropriate to TomKat. Further secondary sources must therefore also be used to fill data gaps.

Note that this Section concerns the IFSM parameter values for TomKat Today only. We hypothesize that some of these values (e.g. those relating to ecological condition of soil and vegetation) will change in future as a result of intensive rotational grazing i.e. in the TomKat Tomorrow scenario. The potential changes are discussed in Section 4.

5.1.2. *Recommendations*

This section presents a description of the IFSM parameters[31], and proposed values for each parameter with supporting rationale and data sources. For more complex parameters, further supporting information is provided in the Appendices. We have relied on a range of reputable secondary data sources, including peer-reviewed studies, university extension services, and specialist soil, ecology, and agriculture organizations such as the Natural Resources Conservation Service (NRCS) and the Food & Agriculture Organization (FAO). Sensitivity analyses will be undertaken to address uncertainty in the secondary data.

This section is divided into:

- Soil parameters (5.1.3);
- Vegetation parameters (5.1.4);
- Grass and forb species parameters (5.1.5);
- Animal and feeding parameters (5.1.6); and,
- Weather data (5.1.7)

For context, we have also included relevant IFSM parameters for which TomKat does have primary measurements (shaded pink).

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[31] Descriptions of the parameters are from the 'User Help' guidance from the IFSM program (v4.1), which is available http://www.ars.usda.gov/services/software/download.htm?softwareid=5 (accessed June 8, 2015).

5.1.3. *Soil parameters*

Table 21: Proposed values for TomKat Today soil parameters

Soil parameter	Description from IFSM	Proposed value	Rationale and main data sources
Available water holding capacity	The amount of water held in the soil profile that is available to the plant when the soil is at field capacity. This is the amount of water or soil moisture between the drained upper limit and the lower limit of the plant extractable water.	99.564mm (available water storage from 0 to 0.8m, which is the maximum rooting depth of annual grass)	Weighted average water holding capacity across soil types for the 776 acres of grassland at TomKat Ranch. Source: TomKat GIS data and NRCS Soil Survey (2014) See Appendix 1 for raw data.
Fraction of available water	The fraction of the available water where the plant begins to experience drought stress.	0.6	Value for extensive grazing/rotational grazing (Allen et al. 1998)
Bare soil albedo	This is the solar reflectivity of the bare soil surface. Typical values range from about 0.1 for dry, dark soils with high organic matter to about 0.3 for light desert sands.	0.13	Iglesias (2006) suggests use of 0.13 when the exact value is unknown.
Soil evaporation coefficient	The coefficient for the upper limit of stage 1 soil evaporation. Typical values range from about 6 mm in sands and heavy shrinking clays, to about 9 mm in loams, and 12 mm in clay loams.	12 mm	Calculating this value requires a significant amount of atmospheric/meteorological data that TomKat does not have for our site. See Appendix 2 for further detail. We therefore propose to use IFSM default value for clay loam (TomKat Ranch is predominantly clay loam).
Runoff curve number	The runoff curve number as defined by the USDA Soil Conservation Service. Typical values for row crops are 60 to 90 where a high number represents poor hydrologic conditions or high runoff.	79	Predominant hydrological soil group at TomKat is C, according to NRCS Soil Survey (2014). Assume pasture quality is 'Fair' based on c. 77% ground cover at TomKat Ranch in 2014. The appropriate runoff curve number is therefore 79 (Cronshey et al. 1986). See Appendix 3 for further detail.
Whole profile drainage coefficient	The whole profile drainage rate coefficient is used to estimate drainage from the profile. Typical values range from 0.3 in clay soils to 0.4 in loam soils to 0.6 in sandy soils.	0.518	Currently, 65% of our soils are considered 'well drained' and 32% are considered 'moderately well drained' (NRCS Soil Survey 2014). According to Iglesias (2006), well drained and moderately well drained soils have whole profile drainage coefficients of 0.4 and 0.6, respectively. This produces a weighted average drainage coefficient for TomKat Ranch of 0.518. We recognize that this is higher than the range defined by IFSM for clay loam soils but believe that the NRCS Soil Survey is a reliable data source. See Appendix 4 for further detail.
Farm phosphorus level	Average concentration of phosphorus [P] in the cropland soil. Levels given represent concentrations of labile phosphorus.	Low (<30 ppm)	TomKat primary measurement

Moist bulk density	The weight per unit volume of the moist soil. Typical values are 1.2 g/cm^3 (75 lb/ft^3) for clay soils to 1.7 g/cm^3 (106 lb/ft^3) for sandy soils. 'Moist' refers to water storage at one-third bar/field capacity.	1.469 (average)	Dry bulk density primary measurements (1.16 g/cm^3) have been converted to moist bulk density using weight wet of soil samples at time of sampling.
Farm topography	Average or typical topography found on the farm. The selection made should reflect the slopes found on the farm designated from relatively flat to very steep.	Moderately steep (15 – 25%)	TomKat primary measurement
Organic carbon content in topsoil	This is the concentration of organic carbon in the soil profile (top 10 cm).	3.42%	TomKat primary measurement from 2015 soil survey
Soil texture	Portion of the soil aggregates that can be considered as silt, clay, and sand.	37.3% silt, 34.3% clay, 28.4% sand	TomKat primary measurement from 2015 soil survey
Soil pH	Typical or average pH of the upper soil layers (top 10 cm).	5.6	TomKat primary measurement from 2015 soil survey
Exchangeable acidity	The exchangeable acidity refers to the amount of H+ ions on cation exchange sites of negatively charged clay and organic matter fractions of the soil. Soil exchangeable acidity is used to determine the amount of lime necessary to increase the soil pH for appropriate crop growth and development. A higher value will use more lime to neutralize the soil. To remove any application of lime, enter zero.	0	TomKat does not use any lime, so we will use value of 0 to ensure that IFSM reflects this practice.

5.1.4. *Vegetation parameters*

Table 22: Proposed values for TomKat Today vegetation parameters

Vegetation parameters	Description from IFSM	Proposed value	Rationale
Grass area	Land area in grass production.	148 ha for TomKat Ranch[32];	TomKat has approximately 314 hectares (776 acres) of pasture. Approximately 49% of TomKat's pasture consists of coyote brush, trees, invasive weeds, poisonous shrubs, and bare ground (according to TomKat vegetation composition data for 2014). Assuming that these areas are not grazeable, 51% of TomKat Ranch is grazeable. Therefore, grass area is 51% * 314 ha = 160 ha. 12 ha are used for grazing

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[32] We may, from time to time, lease land in the local area beyond TomKat Ranch to graze cattle. However, we focus our analysis in this Section on TomKat Ranch only as this is our primary and permanent grazing area.

			horses, therefore 148 ha are available for cattle grazing.
Sward dry matter	The amount of biomass in the grass sward when the simulation begins.	392 kg/ha	Average aboveground plant biomass under grazed conditions between 2007 and 2009 for site in Monterey, California (Skaer et al. 2013)
Sward composition	The long-term average composition of the sward, which can contain species of cool-season grasses, legumes, and forbs (broadleaf plants), as well as warm-season grasses. Sward composition must add up to 100%.	Forb: 14% (*Plantago lanceolata*) Cool-season grass: 86% (*Brachypodium distachyon*)	In 2014, forbs represented 14% of total vegetation at TomKat Ranch. Only one type of cool-season grass can be modelled in IFSM at a time. Currently TomKat Ranch is dominated by annual grass, so we apply characteristics of the dominant annual grass species (*Brachypodium distachyon*) to all non-forb vegetation i.e. 86% of total. See section 5.1.5 for grass characteristics. Note that we expect perennial grasses to dominate vegetation in TomKat Tomorrow. Therefore, for TomKat Tomorrow, we propose to apply the characteristics of the dominant perennial grass species (*Phalaris aquatica*) to all non-forb vegetation. See Section 4 for further detail.
Stand life	The number of years grass is produced in a given field before the field is plowed and replanted to grass or rotated to another crop. A typical value is 3 to 5 years. For permanent or near permanent grass fields, this value should be set high.	40 years	We do not plow our fields, therefore this should be set at a 'high' value. Assume 40 years, which is the assumption applied by Stackhouse-Lawson et al. (2012) for perennial grasses.

5.1.5. *Grass and forb parameters*

A substantial number of grass and forb species parameters are required by IFSM. Many of the parameters are obscure and it was challenging to identify secondary data for the specific grass species that exist at TomKat Ranch. Where no secondary data were found, we propose to use the appropriate IFSM default values. Sensitivity analyses will be undertaken to address uncertainty in the secondary data.

Table 23: Proposed values for TomKat Today annual grass, perennial grass, and forb species parameters

Species parameter	Description in IFSM	Proposed value	Rationale
Species 1: *Brachypodium distachyon* (annual)			
Specific leaf area	The amount of leaf area for a given mass of leaf dry matter. Larger values increase growth rate, which is very sensitive to changes in this parameter.	19.7 m^2/kg leaf dry matter	For a congeneric species (*Brachypodium pinnatum*), from Arredondo & Schnyder (2003)

Max photosynthetic temperature	The maximum temperature at which the species can perform photosynthesis. Above this temperature, no photosynthesis occurs.	35°C	As for other C3 grasses currently in IFSM
Optimum photosynthetic temperature	Temperature at which the species experiences the highest rate of photosynthesis	20°C	As for other C3 grasses currently in IFSM
Min photosynthetic temperature	The minimum temperature at which the species can perform photosynthesis. Below this temperature, no photosynthesis occurs.	0°C	As for other C3 grasses currently in IFSM
Base photosynthetic rate	The maximum rate at which the species performs photosynthesis. Larger values increase growth rate.	14.5 µmol $CO_2/m^2/s$	From Garnier et al (1999)
Temperature effect on photosynthesis	The rate at which photosynthesis increases for each increase in temperature of 1 degree Celsius. Larger values increase growth rate.	1.14 µmol $CO_2/m^2/s/°C$	As for other C3 grasses currently in IFSM
Light extinction coefficient	Degree to which leaves of the species capture sunlight. Larger values increase growth rate. Grasses (narrow leaves, more upright form) tend to have values around 0.5, while legumes and forbs (broader leaves, greater spread) tend to have values around 0.7.	0.5	Standard for grasses according to IFSM
Radiation use efficiency	The amount of biomass produced for each unit of sunlight captured. Larger values increase growth rate, which is sensitive to changes in this parameter.	5 g/MJ total radiation	This is a parameter for crops that is not usually measured for grasses. Values will probably range between 2.6-6.9 (Cristiano et al. 2015) - recommend using 5 as most other grasses in IFSM
Proportion growth sent to shoot	The proportion of daily growth sent to shoots; the remainder is sent to roots. Larger values increase growth rate.	0.7	No data found. Recommend 0.7 as most common for grasses in IFSM
Leaf transmission coefficient	The proportion of intercepted sunlight that passes through a leaf uncaptured. Larger values decrease growth rate.	0.1	As for other C3 grasses currently in IFSM
Maximum rooting depth	The maximum depth of the species' roots in the soil profile. Larger values give the species greater access to soil water and nitrogen.	80 cm	No data found. Recommend 80 cm as most common for grasses in IFSM
Maximum nitrogen concentration	The maximum concentration of nitrogen that plant leaves can accumulate under optimum conditions. Larger values tend to decrease growth rate.	4.80%	As for other C3 grasses currently in IFSM
Species 2: *Phalaris aquatica* (perennial)			
Specific leaf area	As defined for species 1 above	30 m^2/kg leaf dry matter	For a congeneric species (*Phalaris arundinacea)*, from Sugiyama (2005)
Max photosynthetic temperature	As defined for species 1 above	35°C	As for other C3 grasses currently in IFSM

Optimum photosynthetic temperature	As defined for species 1 above	20°C	As for other C3 grasses currently in IFSM
Min photosynthetic temperature	As defined for species 1 above	0°C	As for other C3 grasses currently in IFSM
Base photosynthetic rate	As defined for species 1 above	15.8 µmol $CO_2/m^2/s$	From Lilley et al. (2001)
Temperature effect on photosynthesis	As defined for species 1 above	1.14 µmol $CO_2/m^2/s/°C$	As for other C3 grasses currently in IFSM
Light extinction coefficient	As defined for species 1 above	0.5	Standard for grasses according to IFSM
Radiation use efficiency	As defined for species 1 above	5 g/MJ total radiation	This is a parameter for crops that is not usually measured for grasses. Values will probably range between 2.6-6.9 - recommend using 5 as most other grasses in IFSM (Cristiano et al. 2015)
Proportion growth sent to shoot	As defined for species 1 above	0.59	Lilley et al. (2001)
Leaf transmission coefficient	As defined for species 1 above	0.1	As for other C3 grasses currently in IFSM
Maximum rooting depth	As defined for species 1 above	120 cm	Cox et al (2006) suggest perennial roots are deeper than annuals, around 50% longer based on image (80cm*150% = 120 cm)
Maximum nitrogen concentration	As defined for species 1 above	4.80%	As for other C3 grasses currently in IFSM
Species 3: *Plantago lanceolata* (forb)			
Specific leaf area	As defined for species 1 above	21.8 m^2/kg leaf dry matter	Average of two measurements (taken in April and July) in a grassland environment (Poorter & De Jong 1999)
Max photosynthetic temperature	As defined for species 1 above	35°C	From Teramura & Strain (1979)
Optimum photosynthetic temperature	As defined for species 1 above	23°C	From Teramura & Strain (1979)
Min photosynthetic temperature	As defined for species 1 above	0°C	As for other C3 forb in IFSM

Base photosynthetic rate	As defined for species 1 above	16 µmol $CO_2/m^2/s$	Average of 2 figures (8 and 23.9) from Staddon et al (1999) and Teramura & Strain (1979), respectively.
Temperature effect on photosynthesis	As defined for species 1 above	1.14 µmol $CO_2/m^2/s/°C$	As for other C3 forb in IFSM
Light extinction coefficient	As defined for species 1 above	0.66	As for other C3 forb in IFSM - appear to have similar structure
Radiation use efficiency	As defined for species 1 above	5 g/MJ total radiation	This is a parameter for crops that is not usually measured for forbs. Values will probably range between 2.6-6.9 - recommend using 5 as other forb in IFSM
Proportion growth sent to shoot	As defined for species 1 above	0.68	From Lambers et al (1981)
Leaf transmission coefficient	As defined for species 1 above	0.1	As for other C3 forb in IFSM
Maximum rooting depth	As defined for species 1 above	20 cm	Unable to find exact figure, but images from Berendse (1981)suggest that its roots are around 20 cm.
Maximum nitrogen concentration	As defined for species 1 above	4.80%	As for other C3 forb in IFSM

5.1.6. ***Animal and feeding parameters***

Sensitivity analyses will be undertaken to address uncertainty in the secondary data.

Table 24: Proposed values for TomKat Today animal and feeding parameters

Cattle parameters	Description in IFSM	Proposed value	Rationale
Peak milk yield	The highest quantity of milk produced daily by a cow during a lactation cycle. Peak milk usually happens around 30 to 60 days in lactation with a slow decline during the remainder of the cycle.	8.0 kg/day	From Jenkins et al. (2000)
Phosphorus and protein feeding levels	By default, all animal diets are formulated to meet phosphorus and protein requirements as recommended by the NRC guidelines on Nutrient Requirements for Dairy Cattle. This adjustment allows diets to be formulated using more or less phosphorus/protein than normally recommended.	100% of NRC recommendation	Assume our cattle receive 100% of the amount recommended by the NRC on the basis that no observed evidence of deficiencies in the herd.
Genetic influence on	This is an adjustment factor for the breed of the animal on the energy requirements for	1	Equal to that of Angus or Hereford in IFSM and such characteristics are not

maintenance energy requirement	maintenance. The factor ranges from 0.90 to 1.20. These differences are due to varying proportions of soft tissue relative to body weight in the various breeds. Higher proportions of soft tissue increase the net metabolism of the animal, especially the liver and digestive tract.		substantially affected by heterosis (Hough n.d.).
Genetic influence on fiber intake capacity	A fiber intake capacity is calculated in the model for each animal group in the herd. The factor entered here will increase or decrease the internally defined capacity for all animal groups. This factor provides the user with some control over the maximum forage a breed will consume.	1.025	Average of that of Angus and Hereford in IFSM and such characteristics are not substantially affected by heterosis (Hough n.d.).
Genetic factor for carcass leanness	A genetic factor for the breed that sets the leanness of the carcass during the growth of the animal.	6	Williams et al. (1995, p.670)
Protein, fat, and energy supplements	Crude protein, full fat seed, and energy supplements given to the animals	None	TomKat primary measurement
Breed	Breed of animal raised on the farm	Angus Hereford cross	TomKat primary measurement
Mature cow shrunk body weight	96% of the actual weight for a fully-grown cow of this breed	675 kg	TomKat primary measurement (1,488 lbs)
Calf birth weight	The average weight at birth of all calves in the herd.	29.5 kg	TomKat primary measurement (65 lbs)
First lactation cows	The percentage of cows that are culled or replaced with first lactation animals each year. Reasons for culling may include breeding problems, alimentary or metabolic diseases, age, etc. A typical response is 20 to 30%.	10%	TomKat primary measurement
Calving month	The month in which the majority of the cows in the herd calve.	June	TomKat primary measurement
Age at weaning	Calves will be weaned at the specified age. The age selected must be between 5 and 8 months.	8 months	TomKat primary measurement
Stocker period	Number of months between weaning of calves and the beginning of the finishing period.	11 months	TomKat primary measurement
Finishing period	Number of months cattle are fed a finishing ration	7 months	TomKat primary measurement
Finish shrunk body goal weight	Weight calculated at the body fat endpoint selected for finished steers and heifers, which should be 96% of actual weight at this point. When both steers and heifers are finished together, the weight selected should represent an average for the group.	544 kg	TomKat primary measurement (1,200 lbs)

5.1.7. *Weather data*

The IFSM simulation is performed on a daily time-step using weather data read from a 'weather file'. The weather file consists of daily weather data for at least one year covering: total solar radiation, mean temperature, maximum temperature, minimum temperature, total precipitation, and average wind speed (Rotz et al. 2014). While IFSM has existing weather files for a number of locations, including 5 locations in California, none of these are appropriate for representing the coastal Californian microclimate at TomKat Ranch.

We have therefore constructed our own weather file. This is based on the 'typical meteorological year' dataset produced by National Renewable Energy Laboratory for a weather station in Monterey, California (National Renewable Energy Laboratory 2015), which provides weather data on an hourly basis for a one-year period, which is intended to represent 'typical' conditions. This dataset was chosen because of its completeness (all required weather data from a single data source) and its coastal California climate.

However, we identified that the annual precipitation from this dataset (approximately 200mm) is significantly lower than average annual precipitation figures from other data sources (e.g. 537mm from US Climate Data (2015); 501 mm from Desert Research Institute (2015)), and indeed much lower than that recorded at TomKat over the last four years (c. 600mm).

We have therefore adjusted the daily precipitation and temperature data in the NREL dataset to reflect TomKat's monthly average maximum temperature, minimum temperature, and precipitation recorded since 2010. Table 25 provides summary weather statistics for our final weather file.

Table 25: Summary weather statistics

Weather parameter	Value for TomKat
Annual precipitation	608 mm
Average mean temperature	12.3°C
Average max temperature	16°C
Average min temperature	9.4°C
Average wind speed	2.7 m/s
Average solar radiation	17 MJ/m^2

IFSM does not specifically account for fog. This is a limitation of the model that will be included in the limitations section. However, the calibration process should help account for any significant changes in forage production due to fog.

6. Environmental impact valuation

This section sets out our methodologies for identifying, quantifying and valuing the societal cost of the five environmental impacts in scope. The methodologies presented here are based on ones developed in conjunction with the academic and business communities. We have adapted and tailored the methodologies for application at TomKat Ranch by adjusting the scope to match the most important impacts in cattle ranching and using California-specific data wherever possible. In the interests of readability and relative brevity we have summarized the methodologies and focused on the key points[33].

6.1. Greenhouse gases

6.1.1. *The environmental impact of greenhouse gases*

The earth's atmosphere shields us from harmful radiation, provides us with air to breathe and traps enough heat from the sun to enable the planet to support complex life. Scientists have long been aware of this essential 'greenhouse effect,' but, in recent decades, they have become increasingly concerned about potential impact of changes in the composition of the atmosphere on the amount of heat trapped.

Data now show conclusively that the earth is warming and has been for some time. In the last 100 years, global average surface temperatures have increased by 0.89 degrees Celsius (IPCC 2013), and scientists have 'very strong confidence' that the net effect of human activities (and the resulting increase in atmospheric greenhouse gas (GHG) concentration) has contributed to this warming (IPCC 2007).

According to the IPCC's Fifth Assessment Report on Climate Change (IPCC 2013), there is 'high agreement and much evidence' that global GHG emissions will continue to grow over the next few decades. Under a range of scenarios, the IPCC's Fifth Assessment Report projects that the increase in global surface temperatures will be between 2.6 and 4.8 degrees Celsius by the end of the 21st century. The physical impacts (and resultant societal impacts) of this climate change are as diverse as its causes. Examples of the projected impacts are listed in
Table 26.

Table 26: Projected impacts of climate change (IPCC 2007)

Impact areas	Examples of projected impacts
Freshwater resources and their management	• Drought-affected areas will likely increase in extent and heavy precipitation events, which are very likely to increase in frequency, will augment flood risk. • In this century, water supplies stored in glaciers and snow cover are projected to decline. This will reduce water availability in regions supplied by meltwater from major mountain ranges, which is where more than one-sixth of the world's population currently live.
Ecosystems	• Resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g. flooding, drought, wildfire, insects, ocean acidification) and other global drivers of change (e.g. land-use change, pollution, over-exploitation of resources). • Approximately 20-30% of plant and animal species (assessed so far) are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C.

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[33] For comprehensive and fully referenced versions of these methodologies please refer to: www.pwc.co.uk/naturalcapital where the long form impact valuation methodology papers can be downloaded.

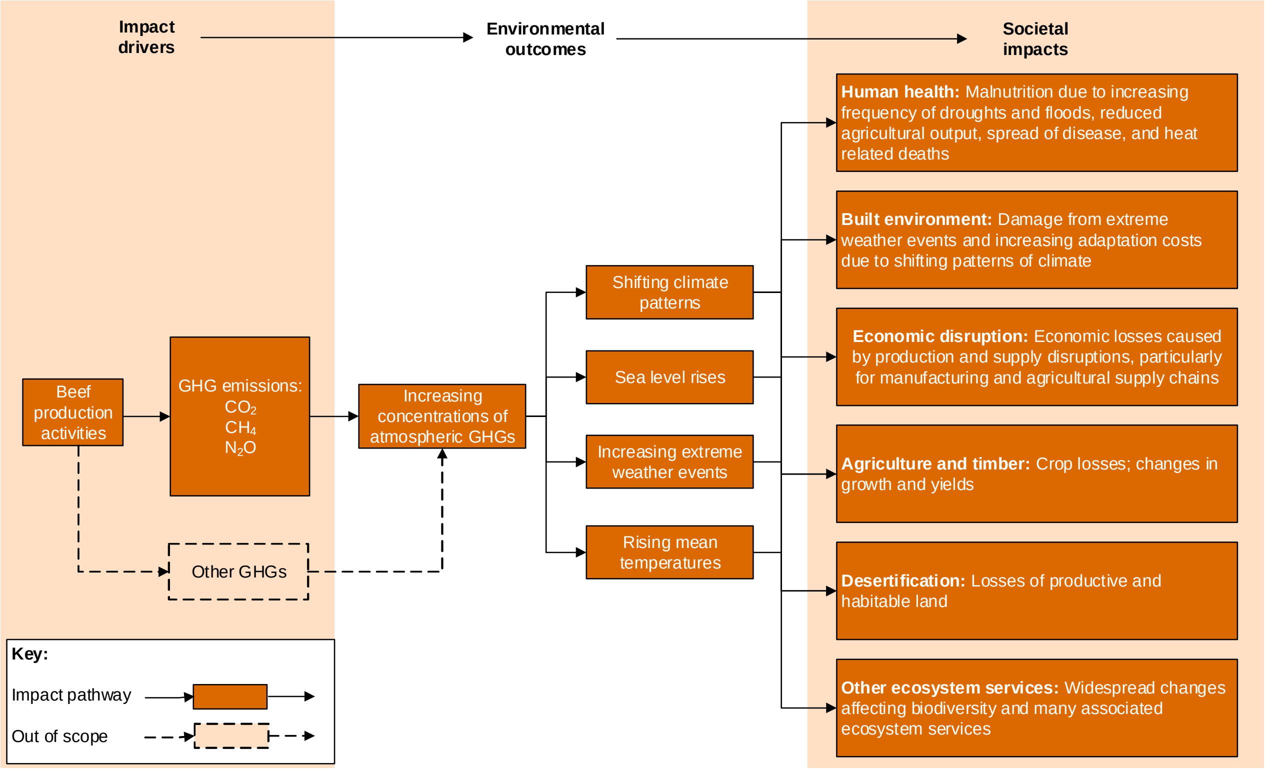
Agriculture	• Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1-3°C. Above 3°C, it is projected to decrease. • Increases in the frequency of droughts and floods are projected to affect local crop production negatively, especially in subsistence sectors at low latitudes.
Coastal systems and low-lying areas	• Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea-level rise. The effect will be exacerbated by increasing human-induced pressures on coastal areas. • Many millions more people are projected to be flooded every year due to sea-level rise by the 2080s. The numbers affected will be largest in the mega-deltas of Asia and Africa, while small islands are also especially vulnerable. • Adaptation for coasts will be more challenging in developing countries than in developed countries due, in particular, to the high costs of many forms of adaptation.
Industry, settlement and society	• Costs and benefits of climate change for industry, settlement and society will vary widely by location and scale. In the aggregate however, net effects will tend to be increasingly negative, the larger the change in climate. • Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities and are more dependent on climate-sensitive resources such as local water and food supplies.
Health	• Projected climate change-related exposures are likely to affect the health of millions of people, particularly those with low adaptive capacity. Particular causes include increases in malnutrition, increasing deaths due to floods, heat-waves, storms, fires and droughts; and altered spatial distribution of some infectious disease vectors. • Studies in temperate areas have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. Overall however, it is expected that these benefits will be outweighed by the negative health effects of rising temperatures worldwide, especially in developing countries.

6.1.2. *Impact pathway*

In order to value these environmental impacts of GHGs, we need to understand how the release of GHGs into the atmosphere affects humans. Our impact pathway (see Figure 5) describes how these factors influence environmental outcomes and, subsequently, people. Our impact pathway framework consists of three elements:

- Impact drivers: the quantity of GHGs produced;
- Environmental outcomes: the ways in which our climate is changing; and
- Societal impacts: these include negative impacts on human health, increased food and energy costs (which also have an economic impact), loss of coastal land and reduced enjoyment of the environment.

Figure 5: Greenhouse gases impact pathway



6.1.3. *GHGs from cattle ranching*

The main GHGs produced on the Ranch are methane (CH4), nitrous oxide (N2O) and carbon dioxide (CO2). CH4 is produced by enteric fermentation (a digestive process occurring in the animal's rumen) and from manure deposited by grazing animals. N2O is produced by nitrification and denitrification processes in the soil, which are influenced by the presence of manure and other fertilizers deposited on pasture. CO2 is generated from the operation of farm buildings, machinery, and vehicles. Land management practices can result in either losses or gains (sequestration) of CO2 in the form of soil organic carbon (Desjardins et al. 2012).

'Upstream' GHGs are released in the production and transportation of ranch inputs, including feed, fuel, seeds, fertilizers, pesticides, hormones, machinery and vehicles.

'Downstream' GHGs are those released in packing, packaging, distribution and consumption of beef.

In this analysis, GHGs are expressed in CO2 equivalent units (CO2e), which takes into account the different global warming potential (GWP) of each type of gas. We used a GWP value of 25 and 298 for CH4 and N2O, respectively (IPCC 2007).

6.1.4. *Approach to quantifying GHGs*

The approach to quantifying GHGs across the value chain is explained in Section 2.

6.1.5. ***Approach to valuing GHGs***

The core of the methodology to value the impact of GHGs revolves around identifying an appropriate estimate of the societal cost of carbon (SCC) (i.e., the current and future economic damage from emission of one unit of CO2e) to estimate the value of the current and future impacts of GHG emissions.

6.1.5.1. Why the societal cost of carbon?

We select the SCC as a better approximation of the impact on society from GHGs than the marginal abatement cost (MAC) or market prices. The MAC does not measure impact on society, showing instead the cost of reducing that impact at a point in time given prevailing technology. Carbon market prices do not currently reflect the value of the impact on society as a result of GHG emissions. Instead, in the case of the European Union Emissions Trading Scheme (EU ETS) (for example), prices reflect the equilibrium in a relatively inflexible regulated market. As such, they give the current private cost of GHG emissions for regulated installations, but are generally a poor proxy for the societal cost of those emissions.

6.1.5.2. Estimating the societal cost of carbon

Arriving at a primary estimate of the societal cost of carbon typically involves a number of complex steps:

(1) Selecting an emissions scenario (typically one of the IPCC scenarios)

(2) Constructing a climate model to project the likely future changes in climate

(3) Developing impact assessment models to quantify associated impacts on society

(4) Estimating the total economic costs associated with these impacts

(5) Discounting back the total cost estimate to the present-day using a social discount rate, and finally

(6) Apportioning the net present value of climate damages according to the volume of anthropogenic GHGs emitted.

The result is an estimate of the societal cost of carbon (SCC) per metric ton of CO_2 equivalent (tCO_2e).

To produce our estimate of the SCC, we chose to analyze the extensive academic literature which already exists on the subject. Alternative approaches would have involved either: a) undertaking a new climate modelling and valuation exercise from first principles or b) selecting an SCC estimate from a single study.

We chose our meta-analytic approach in preference to the alternatives because, while the SCC has been subject to a significant amount of research by academics and government agencies - hence a novel study in the absence of new information would be of marginal benefit; there is not a single preferred approach – hence selecting a single study would be difficult to justify. Our approach is not a purely statistical meta-analysis (since it incorporates a number of non-statistical factors), but it shares some of the key benefits of a conventional statistical meta-analysis, particularly the ability to incorporate the results of multiple studies applying a range of different methods and scenarios. It also has the significant advantage that once a set of rules for selecting a sub-set of studies is defined, an automatic and un-biased mechanism to update the SCC estimate over time (as new research becomes available) is also established.

Based on our meta-analysis we estimate an SCC of $94/tCO2e for GHGs emitted in 2015. The table below summarizes our approach to analyzing SCC estimates from the academic literature.

6.1.5.3. Our meta-analytic approach

Factor	Methodological choice in estimating SCC	Assumptions and justification
Selection of a restricted sub-set of SCC estimates		
Quality of study	Only estimates from peer reviewed studies will be used.	Peer review is the only widely accepted measure of quality applicable to studies of the societal cost of carbon. The significant and apparently systematic difference in values (peer reviewed values are typically lower) suggests that this is an important criterion.
Age of study	Only estimates from the ten most recently published peer-reviewed studies in our dataset are included.	Studies and estimates are generally perceived to have improved over time as both climate modelling and economic damage assessment methods have improved. We therefore deem it appropriate to focus on more recent estimates of the SCC, while maintaining a reasonable number of estimates to reflect the diversity of views about underlying assumptions. In order to do this, we use estimates from the ten most recently published peer-reviewed studies that conform to our methodology choices. While recognizing that ten studies is a somewhat arbitrary figure, we note that choosing a study age criterion based on a number of studies has the additional benefit of providing a useful rule for future updates to the SCC based on newly published studies.
Discount rate	Only estimates that apply Pure Rate of Time Preference (PRTP) = 0% are included. We do not select SCC estimates according to the values they use for future economic growth rates and income elasticity of marginal utility.	A discount rate is used to convert future damage costs to their present value. In established economic theory (Ramsey 1928), the discount rate includes the Pure Rate of Time Preference (PRTP), a forecast of economic growth, and the marginal elasticity of utility with respect to income. We consider it ethically defensible and aligned with notions of inter-generational equity commonly found in the climate change literature to value the wellbeing of future generations equally to our own. It is not possible to select a subset of estimates that use specific values for income elasticity of marginal utility and economic growth rate because not all studies disclose this information. However, those that do disclose their assumptions show a sample average of 2.5%.
Treatment of outliers	Estimates more than three standard deviations from the mean are excluded.	Eliminating outliers helps to prevent extreme values from unduly distorting ‘sample statistics’. However, the possibility of catastrophic climate outcomes (however remote) is generally accepted, and estimates of the SCC have been observed to follow a ‘fat-tailed’ distribution. We acknowledge the likelihood of this type of distribution by including estimates up to three standard deviations from the mean, but consider estimates outside this range to be true outliers and exclude them from our sample statistics on this basis.
Equity weighting	We do not select for SCC estimates according to the equity weighting used.	Equity weighting adjusts societal costs between different economic groups in underlying studies. No consensus exists on the appropriate method or degree of ‘equity weighting’ to use. We note that around 33% of our sub-set use some form of equity weighting and the overall effect on the results is modest.
Damage valuation approach	We do not select for SCC estimates according to the damage valuation	Variation in underlying studies is relatively limited and there is no consensus on the preferred method.

	approach used to derive the economic cost of climate change.	

Calculation of SCC from the restricted population of estimates

Monetary inflation	Monetary inflation has been addressed by inflating each SCC estimate using World PPP-adjusted GDP deflators.	The value of a given monetary unit typically decreases over time as a result of monetary inflation. As the underlying studies relate to different years, the estimates need to be adjusted for monetary inflation to be comparable. Most studies explicitly or implicitly assume constant real exchange rates into the future. In practice real exchange rates have varied materially in the past twenty years; for this reason, World PPP adjusted GDP deflators are calculated for inflating older SCC estimates.
Growth rate of SCC over time	Growth rate of SCC assumed to be 3% per year.	Because the profile of anticipated climate damages is weighted into the future, and GHGs reside in the atmosphere for a limited period, the climate impact of an additional ton of CO_2e rises over time. Three percent is the mid-point of the IPCC estimated range (2 – 4%) for this rate of increase.
Unit conversion	Conversion of \$/tC to \$/tCO_2e has been carried out by multiplying societal costs expressed in tC by the fraction 12⁄44.	Estimates of the SCC from the academic literature are typically expressed in: \$/tCe. We wish to present our results in the industry-standard units, \$$tCO_2e$. We therefore adjust for the difference in weight between a single atom of carbon (atomic mass = 12u) and a molecule of CO_2 (molecular mass = 44u).
Weighting of estimates	A multiple estimates weighting has been applied to values from studies which contain more than one estimate.	Studies with multiple estimates are weighted such that the sum of weightings for all estimates from a single study is 1. This is as applied by Tol (2011) and prevents individual studies containing large numbers of estimates crowding the sample and distorting the average SCC obtained towards the methods they employed. The technique also attempts to reflect the confidence placed by the author in each estimate.
Distribution of data	No fitted distributions are applied for the purpose of producing the SCC.	The sub-set of estimates selected (after applying the criteria set out above) does not clearly fit a specific distribution. We therefore consider it more transparent to use unfitted data to derive our averages.
Sample statistics	We present both the arithmetic mean and the median results of our meta-analysis and leave the choice of mean or median to the user. Our default suggestion is to use the mean.	There are valid statistical and ethical reasons for choosing either a mean or median value in this context. The mean takes more account of very high estimates derived from potentially catastrophic climate scenarios and therefore reflects a more precautionary approach to potential climate change impacts. The median, by contrast, is less affected by a few very high values and should therefore better reflect the consensus view, but takes limited account of catastrophic scenarios. Whichever value is chosen, the implications of using the other can be tested using sensitivity analysis.

6.2. *Water consumption*

6.2.1. *The environmental impact of water consumption*

The marginal value to society of consuming water depends on how plentiful the supply of it is and how much (and what kind of) competition there is between users for water.

This section provides a brief introduction to the different potential impacts of industrial water use in general.

Where water use reduces available clean water for other users reliant on the same source, the societal impacts potentially include:

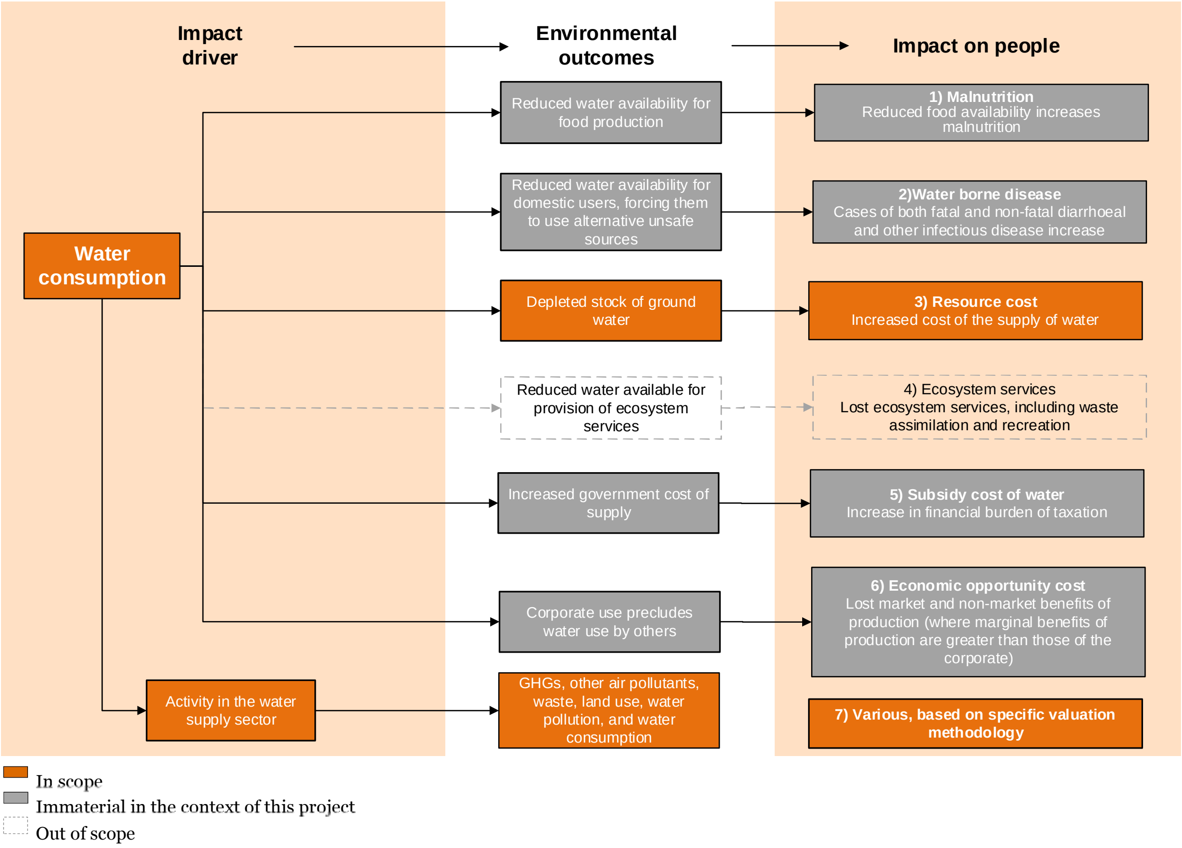
- **The environmental impacts which arise from water supply:** The supply of water prior to use requires energy and raw materials which have environmental impacts, for example greenhouse gas (GHG) emissions from desalination.
- **Resource depletion:** Some communities are dependent on groundwater and are extracting it at an unsustainable rate leading to groundwater depletion and an inflow of saline water. Over exploitation of non-renewable water supplies will lead to future impacts associated with the increased scarcity and cost of supply, unless other sources are secured.
- **The cost to the public finances of any subsidy associated with the provision of water:** Water pricing does not always reflect the full resource cost of its supply, and is frequently subsidised. Water use, therefore, has the potential to increase the burden on tax payers.
- **The impact on human health - malnutrition:** In water scarce areas, water use by one party may reduce the water available to agricultural users thereby reducing yields and causing direct economic losses. In areas dependent on local food production this may also lead to increases in malnutrition.
- **The impact on human health - infectious water-borne diseases:** A reduction in clean water availability may force people to use other water sources. Depending on its quality, this may lead to cases of diarrhoea and other water-borne diseases.
- **Other ecosystem services:** Removal of fresh surface water can reduce the functioning of ecosystems, particularly in riparian areas. The associated loss of ecosystem services may have negative consequences for the local population, including market and non-market losses from fishing and recreation, for example.

6.2.2. *Impact pathway*

In order to quantify the impacts of water consumption, we need to understand how that consumption affects society. We use impact pathways to depict the causal links between water use, its environmental impacts and the resulting societal outcomes.

Figure 6 presents this impact for our analysis. Below we discuss why these impacts were selected.

Figure 6: Water consumption impact pathway



Relevant water consumption for this project is occurring in California and Iowa (counterfactual feed). We therefore selected the relevant sections of the impact pathway based on how water consumption is impacting society in those two regions.

- California Central Valley is one of the biggest aquifers in the world. Richey et al (2015) quantified the level of groundwater stress in the thirty seven largest aquifers in the world. The study, relying on satellite technology, concluded that California Central Valley is facing a high level stress due to too much abstraction. We therefore included groundwater depletion in our assessment for California.
- A portion of TomKat water consumption relies on the water network or on water abstraction processes. We therefore included GHGs emissions from water supply.
- Other sections of the impact pathway were not included as they are either not relevant in the USA or for entities in the agricultural sector.

6.2.3. *Water use in a beef production system*

Water is consumed at multiple stages of the beef production value chain for the following purposes:

- Water use related to drinking and other on-farm activities;
- Water footprint of the feed;
- Water footprint associated with all the other processes on which a beef farming system depend (e.g. raw material extraction, hormone production).

6.2.4. *Approach to quantifying water consumption*

The approach to quantifying water consumption across the value chain is explained in Section 2.

6.2.5. *Approach to valuing water consumption*

Impacts associated with groundwater depletion

Based on current groundwater consumption in California, we calculated how much it would cost society to reduce its groundwater consumption to sustainable levels. Based on the United Nations water scarcity standards, we consider that a sustainable level of groundwater consumption corresponds to a water scarcity ratio of 10% (Richey, A.S. et al., 2015). Water scarcity is defined as the amount of water use divided by the amount of water available. We then consider that the most appropriate technology to replace this excess water consumption is to rely on desalination technology. We therefore rely on desalination cost to estimate groundwater depletion cost. We obtain a value in $ per m3 for the different key value chain locations in California.

We consider that surface water consumption reduces groundwater availability over the long term, especially in regions like California which face periods of drought. We therefore value the total amount of water consumed without distinguishing between groundwater and surface water.

As groundwater depletion is not considered to be an issue in Iowa, the societal resource cost of groundwater consumption is assumed to be zero.

Impacts associated with GHG emissions from water supply

We estimate the GHG emissions associated with the water supply sector in the United States using an environmentally extended input-output modelling technique which applies a GHG intensity per unit of output from the sector. We value these impacts by applying PwC's Social Cost of Carbon estimate and divide them by the total water use from municipal water supply or water abstraction to estimate an impact per m^3. We apply this value to the water consumed relying on abstractive processes (i.e. excluding rainwater) to both California and Iowa locations.

6.3. *Excess nutrients*

6.3.1. *The environmental impact of water pollutants*

The impacts of water pollutants are principally local or regional. They are highly dependent on the physical environment and the local demographic exposure. For example, the change in concentration of arsenic following a release depends on the size of the water body and its rate of flow. The extent of its subsequent impact on people depends on the likelihood that the local population will come into contact with polluted water. The most significant water pollutant categories in societal cost terms are listed below. They are sub-divided into 'toxic pollutants,' 'nutrient pollutants', 'pathogens' and 'thermal'. There are numerous individual pollutants that can be categorised into the key areas listed below.

- **Toxic substances:** Both organic and inorganic substances, including heavy metals and chemical compounds which may persist or cause undesirable change in the natural environment, bio-accumulate in the food web and cause adverse effects to human health.
- **Nutrients - Nitrogen (N) and phosphorus (P):** Both are basic building blocks of plant and animal proteins which in elevated concentrations can cause a range of negative effects including algal blooms leading to a lack of available oxygen in the water.
- **Coliforms:** A broad class of bacteria, some of which are harmful disease-causing organisms, such as Escherichia coli (E. coli) can be released, or encouraged to grow, through discharges of inadequately treated sewage.
- **Thermal:** Discharge of water above or below the ambient temperature of natural water bodies can change the ecological balance.

The discharge of pollutants to water bodies increases their concentration in the water body, directly reducing water quality and causing secondary phenomena such as eutrophication. Eutrophication occurs when an excess of nutrients enters a water body leading to dense plant life which starves other life in that water body of oxygen.

These changes can adversely affect people in several ways:

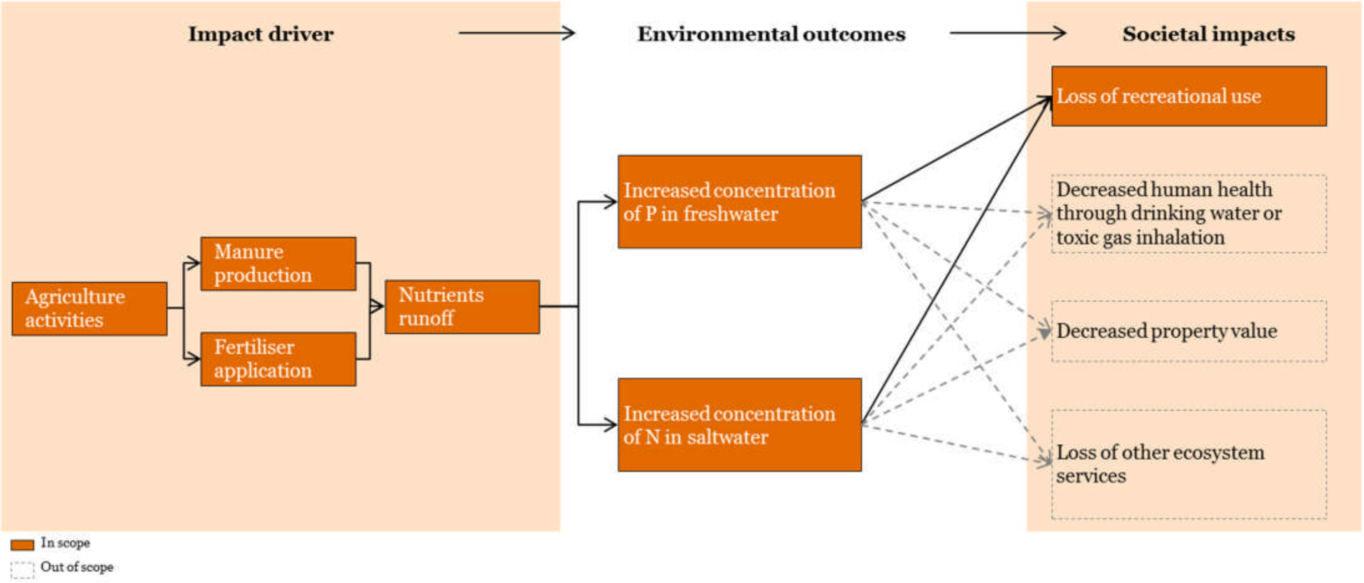
- **Human health impacts:** The build-up of toxins in the human body due to prolonged ingestion of contaminated water or food can cause acute illness, cancer and a host of other health conditions.
- **Impaired recreation value:** The nutrient enrichment of waters can cause excessive macrophyte growth leading to eutrophication. This can affect the recreational use of the water body due to health impacts from toxic blooms, water congestion from excessive vegetative growth, unfavourable appearance and/ or unpleasant odours.
- **Property values:** Eutrophication of water bodies can also affect the potential value of adjacent property (Krysel et al. 2003). The academic literature suggests that leisure and residential property can be devalued by as much as 20% as a result of consistently poor physical water quality (Wood and Handley, 1999).
- **Fish stocks:** Eutrophication reduces the oxygen content of water and can lead to economic losses due to decreased fish yield and changes in species composition. Annual losses to the commercial fishing and shellfish industry from nutrient pollution – attributable to lower yields from oxygen-starved waters and fluctuations in consumer confidence of tainted seafood – are estimated in the United States to be over $40 million annually (Hoagland and Scatasta, 2006).
- **Livestock:** Changes in the toxic concentration of certain chemicals in potable water can negatively impact the health of livestock, leading to reduced production or quality of meat.
- **Agriculture:** Changes in the toxic concentration of certain chemicals in irrigated water can negatively impact the growth of crops, leading to reduced yields and could increase rates of malnutrition in food scarce areas.

The main sources of water pollutants for a beef production system are from fertilizers (animal and artificial) and pesticides. This section focuses on excess nutrients. Pesticides are assessed separately for materiality.

6.3.2. *Impact pathway for nutrients*

Figure 7 illustrates the impact pathway of nutrients through eutrophication. The loss of recreational use is the only societal impact with an established methodology allowing water pollutants valuation. The other societal impacts were therefore not included in the valuation scope.

Figure 7: Excess nutrients impact pathway



6.3.3. *Nutrients in a beef production system*

Nutrients such as nitrogen and phosphorus are naturally parts of aquatic systems. Various human activities can release nitrogen and phosphorus in the environment and cause excess nutrients issues. Those activities or nutrients sources are agriculture, the use of fossil fuels, domestic use of fertilisers and detergents, sewage and urban run-off.

In the case of a beef production system, nutrients can be loaded to the environment at the following value chain stages:

- Fertiliser application for feed production;
- Manure production;
- Fossil fuel combustion (increases the amount of nitrogen in the air before potentially reaching waterways).

6.3.4. *Our approach to quantifying nutrients*

The approaches to quantifying upstream and on-ranch nitrogen and phosphorus application are explained in Section 2.

6.3.5. *Our approach to valuing excess nutrients*

Eutrophication is a known issue in Pescadero Creek which is the principal recipient of run-off from TomKat ranch.

Phosphorus is the limiting factor of for algal blooms in freshwater and nitrogen is the limiting factor for coastal water. We therefore developed a valuation methodology for phosphorus running-off to freshwater and nitrogen running-off to coastal water.

Phosphorus' valuation is based on a study from Dodds et al (2009) which quantified the total recreational value loss per year in the United States caused by freshwater eutrophication. We divide this value by total amount of phosphorus applied to crops each year in the United States to obtain a value per kg of phosphorus applied.

Nitrogen's valuation is derived from a study by Birch et al (2008) into recreational value loss in in coastal waters per kg of nitrogen applied.

Adjusted unit transfers of this kind should be used with caution. However, since the values derived are within ranges identified in previous meta-analyses, and the overall impacts of excess nutrients in relation to other impacts considered in this assessment are small, and in the absence of local primary research, we consider this simple method to be appropriate.

6.4. Pesticide application

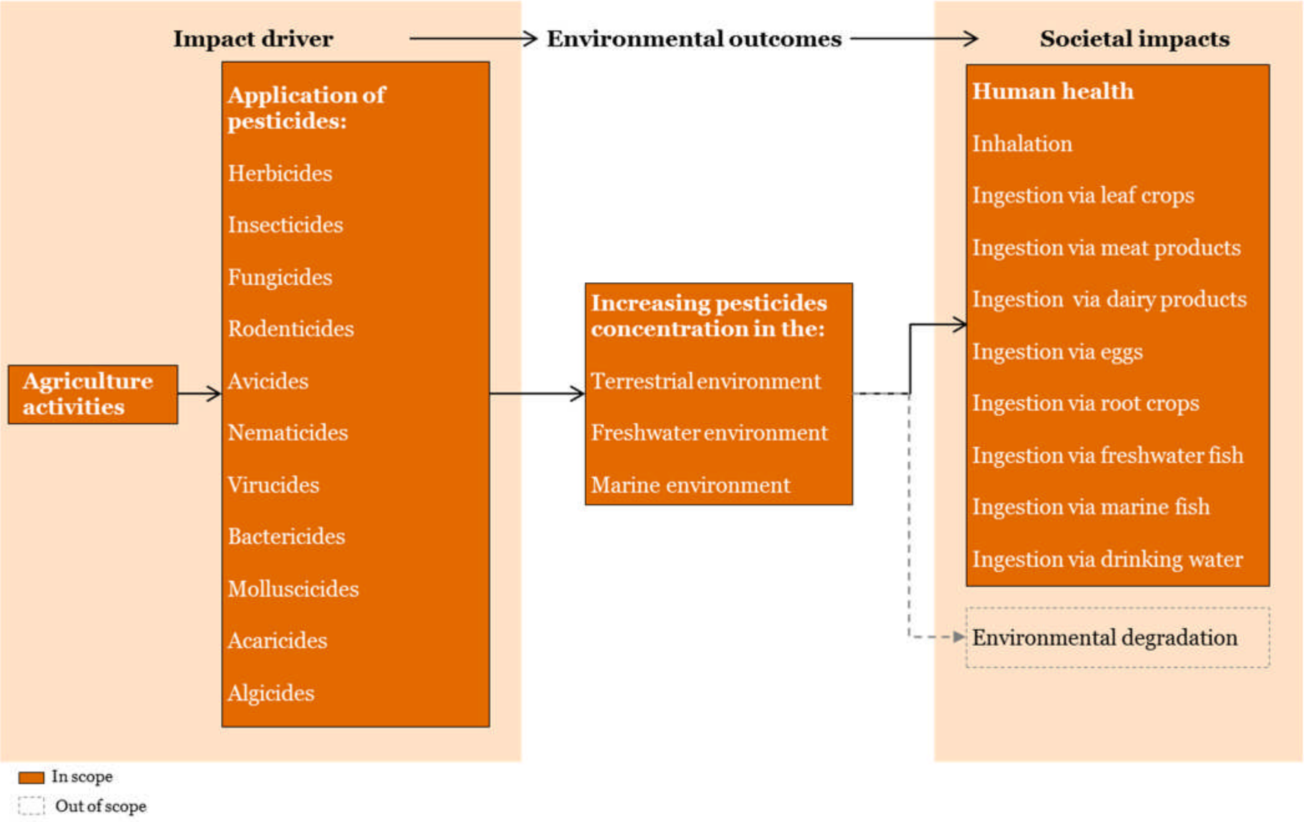
We undertook a materiality assessment of pesticide impacts on human health in the context of beef production systems. Our materiality assessment was based on the amount of pesticides used per type of crops in California and on the ReCiPe methodology for Life Cycle Impact Assessment. We concluded that the impacts of pesticides were not material in this context (at less than five US dollars for feed at a ranch level) and therefore excluded them from the assessment.

Below is a description of the methodology we developed for our materiality assessment.

6.4.1. *Impact pathway of pesticides application*

Figure 8 illustrates pesticides' impacts on human health. People's health can be impacted through inhalation or ingestion.

Figure 8: Pesticides impact pathway



6.4.2. *Pesticides' application in a beef production system*

The main part the value chain of a beef production system where pesticides are applied is during offsite feed production.

6.4.3. *Our approach to quantifying pesticides*

Pesticides were quantified per type of active ingredient and per type of crop based on Pan Pesticides, a Californian pesticides database.

6.4.4. *Our approach to valuing impacts from pesticides' application*

Our pesticides valuation approach draws first on data from ReCiPe (2012), which is a methodology for Life Cycle Impact Assessment. The ReciPe model provides average numbers of Disability Adjusted Life Years (DALYs) caused by pesticide application. A DALY is a measure of disease burden and is expressed as the number of years (or fractions of a year) lost due to ill-health, disability or early death.

Having established the number of DALYs generated as a result of pesticide application, we assign a monetary value to those DALYs to estimate societal cost of pesticides' application. This value is derived from OECD estimates of the Value of Statistical Life.

6.5. Soil improvement

6.5.1. *TomKat Ranch's impact on soil*

TomKat practices intensive rotational grazing, which is a livestock management system designed to emulate natural grazing. Studies have shown that, compared to continuous grazing, rotational grazing results in improvements in soil quality such as reduced bulk density (Teague et al. 2011), reduced run-off (Rotz et al. 2009), and increase in soil organic matter (Sanjari et al. 2008). Additional detail on the predicted impacts of intensive rotational grazing on soil and vegetation at TomKat Ranch is provided in Section 4.

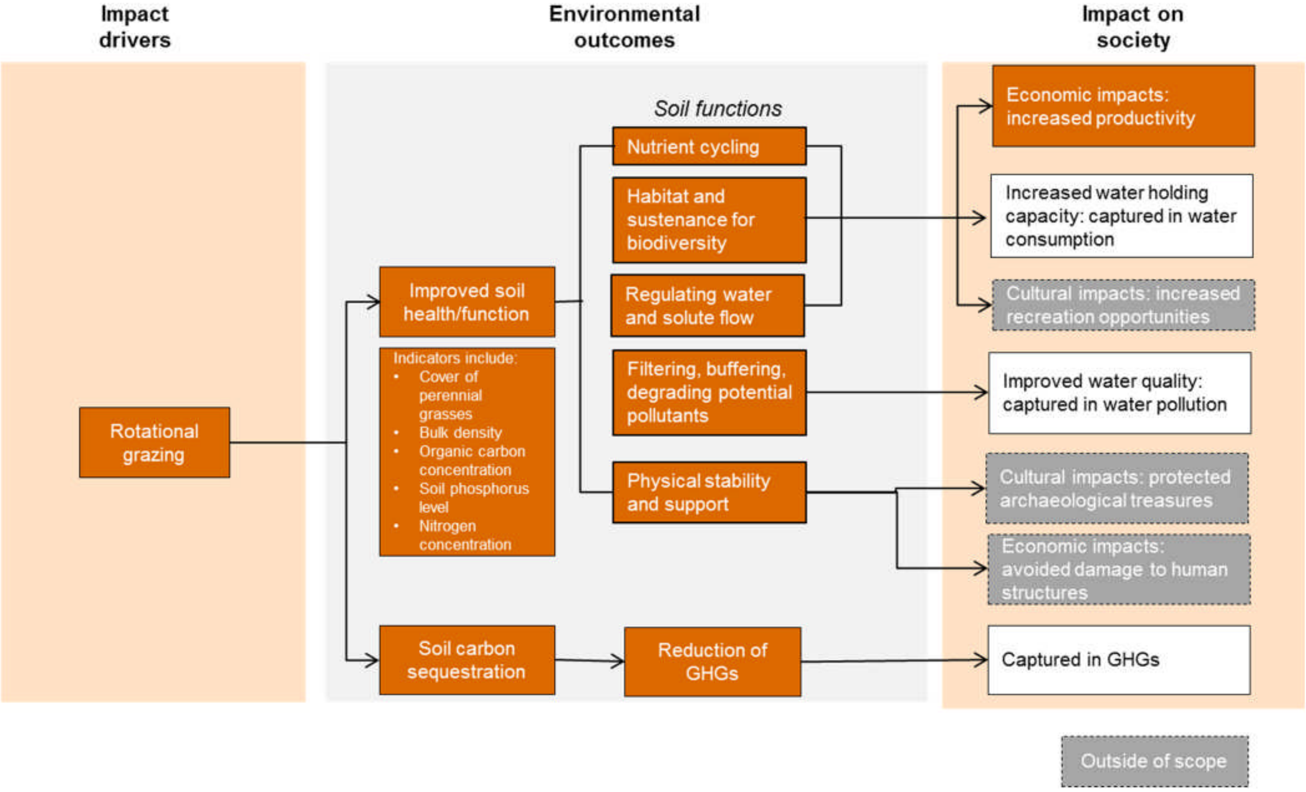
6.5.2. *Impact pathway*

The impact pathway maps physical changes in soil characteristics to improved soil function, which in turn contribute to societal impacts:

- Increased above-ground productivity, contributing to improved animal growth;
- Improved efficiency of water use due to increased water holding capacity;
- Reduced excess nutrients due to improved nutrient filtering;
- Mitigation of climate change through soil carbon sequestration;
- Preserved/improved recreational and heritage opportunities; and
- Avoided damage to man-made structures due to improved soil stability.

The valuation for soil focuses on the first of these impacts i.e. the contribution to productivity of improved soil function. The other significant benefits of soil improvement listed are either captured within other areas of the analysis (Water Consumption, Excess Nutrients, and Greenhouse Gases), or are not relevant/material to TomKat Ranch and therefore outside of the scope of this analysis (no known archaeological treasures nor significant man-made structures at risk on TomKat Ranch).

Figure 9: Soil impact pathway



6.5.3. *Approach to quantification and valuation*

The valuation for soil aims to capture the sustained increase in economic productivity of the land from improvements in soil health and functioning. For TomKat Ranch, increased productivity of the land translates into more forage grown onsite, which leads to cost savings from not having to buy as much hay from suppliers. We proxy the value of increased onsite forage production using the equivalent cost of buying hay i.e. $15/bale.

Reduction in purchased hay requirements X Cost of purchased hay = Value of increased productivity

There are two elements of the productivity value of soil improvement: the private value to the rancher and the wider societal value. The private value to the rancher is captured in the rancher's own financial statements. It is the value of increased productivity now and in the future, discounted at the private discount rate of 10%. However, from society's perspective, the benefit of increased soil productivity 'matters' over a longer time horizon. This is reflected in the societal discount rate (3%)

being lower than the private discount rate[34]. The societal value of soil over 100 years, which is the value of increased productivity over time discounted at 3%, is therefore greater than the private value.

Because this assessment is focused on societal value, the value of Soil in the TIMM analysis only captures the *difference* between the societal and private value of increased productivity. Table 27 provides numerical examples of the value of Soil using an illustrative cost saving of $1,000/year from reduced offsite hay requirements.

Table 27***: Illustrative valuation of soil***

Year	**A. Cost savings (not discounted)**	**B. Cost savings (in $2015) discounted at 10%– *private value of increased productivity***	**C. Cost savings (in $2015) discounted at 3% - *societal value of increased productivity***	**D. In-year value of 'Soil improvement' in TIMM analysis in $2015 (B. – C.)**
2015	$1,000.00	$1,000.00	$1,000.00	$0.00
2016	$1,000.00	$909.09	$970.87	$61.78
2040	$1,000.00	$92.30	$477.61	$385.31
2114	$1,000.00	$0.08	$53.59	$53.51

6.6. *Sediment control*

6.6.1. *TomKat Ranch's impact on watercourse sedimentation*

Loose soil washed into a waterbody impacts aquatic ecosystems and can adversely affect other users of the waterbody, but can be minimized through good land management. TomKat Ranch's sediment management directly impacts Honsinger Creek, which flows through the ranch and later flows into Pescadero Creek.

Pescadero Creek is classified as an "impaired" water course pursuant to section 303(d) of the Clean Water Act. This affects threatened and economically important fish species including steelhead and coho salmon. California's EPA is required to implement a Total Maximum Daily Load (TMDL) plan to reduce sediment, with likely restrictions on land users including ranches (San Francisco Bay Regional Water Quality Control Board 2015). This governmental intervention implies that there is a societal benefit of controlling sediment. Currently the CalEPA are undergoing a consultation process to decide what the Pescadero TMDL plan would involve. Local EPA officers have suggested that TomKat Ranch would be captured as Honsinger Creek is a major tributary of Pescadero Creek.

TomKat Ranch already undertakes the majority of the relevant measures that would likely come into force as part of the TMDL plan, such as restricting grazing animals from riparian areas. On this basis, by protecting its riparian areas and carrying out other practices on site, TomKat is generating a societal benefit that is not captured elsewhere in the TIMM assessment.

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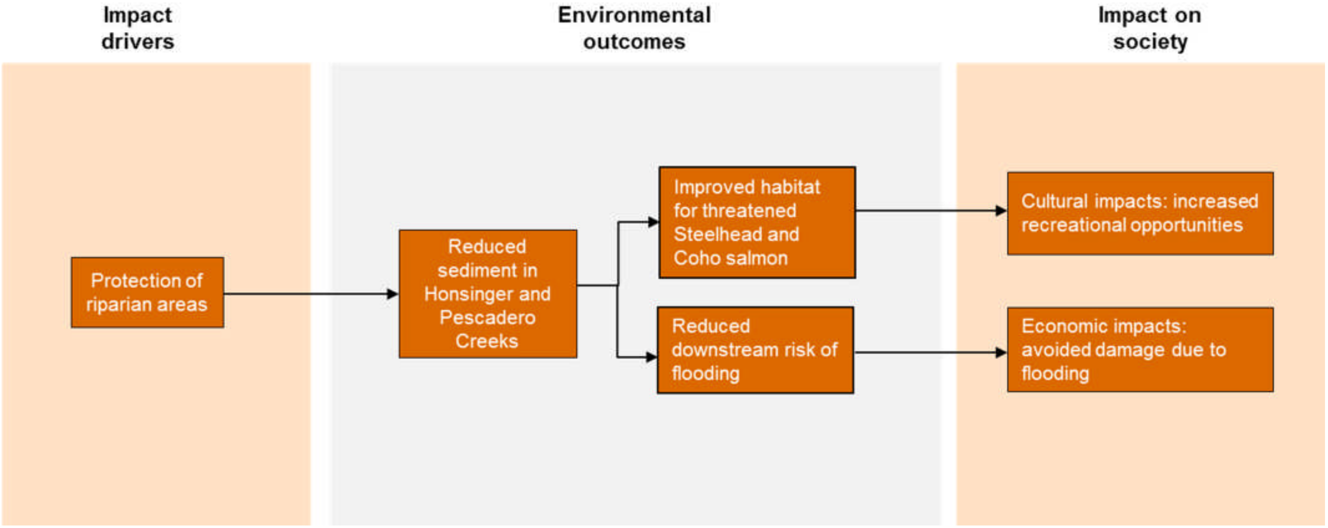
[34] As a society, we are more "patient" than private individuals or organizations, meaning we take into account costs and benefits over a longer time horizon. In other words, as a society we are more willing to postpone consumption today in order to have more to consume later. This translates into the Social Discount Rate (SDR) being lower than the Private Discount Rate (PDR).

6.6.2. *Impact pathway*

Figure 10: Sediment control impact pathway



1.1.1. *Approach to quantification and valuation*

The societal value of restored waterways varies significantly and depends on site-specific factors. We could not find any estimates for the societal value of restoring Pescadero Creek or nearby watersheds. However, government intervention implies that the EPA has judged the benefit of sediment control to outweigh the costs. On this basis, the total costs of implementing the TMDL can be used as a proxy for the lower bound of the benefits generated by sediment control measures, and we can estimate the societal benefit that can be attributed to TomKat Ranch's protection of riparian areas.

While projected costs for a Pescadero TMDL plan have not yet been published, a TMDL plan recently implemented in the Napa Valley watershed (584 km^2) is expected to cost $1.9 million to $3.4 million per year for agricultural land users (San Francisco Bay Regional Water Quality Control Board 2007). We used the mid-point estimate ($2.65 million) and adjusted for inflation to 2015 USD ($3.03m) to estimate the restoration cost for an area of watershed equivalent in size to TomKat Ranch.

We rely on the costs of the Napa Valley project being accurately predicted, and that Pescadero Creek would require similar interventions. The estimate could be improved in future using actual costs faced by other ranchers in the Pescadero creek watershed if and when available. We assume equivalence of the Napa Valley and Pescadero Creek watersheds. We acknowledge that Napa Valley watershed likely has a higher proportion of high worth vineyards (11.5%) than Pescadero Creek watershed, but it is not clear what impact this has on the cost of implementing sediment control measures.

6.7. *Habitat conservation*

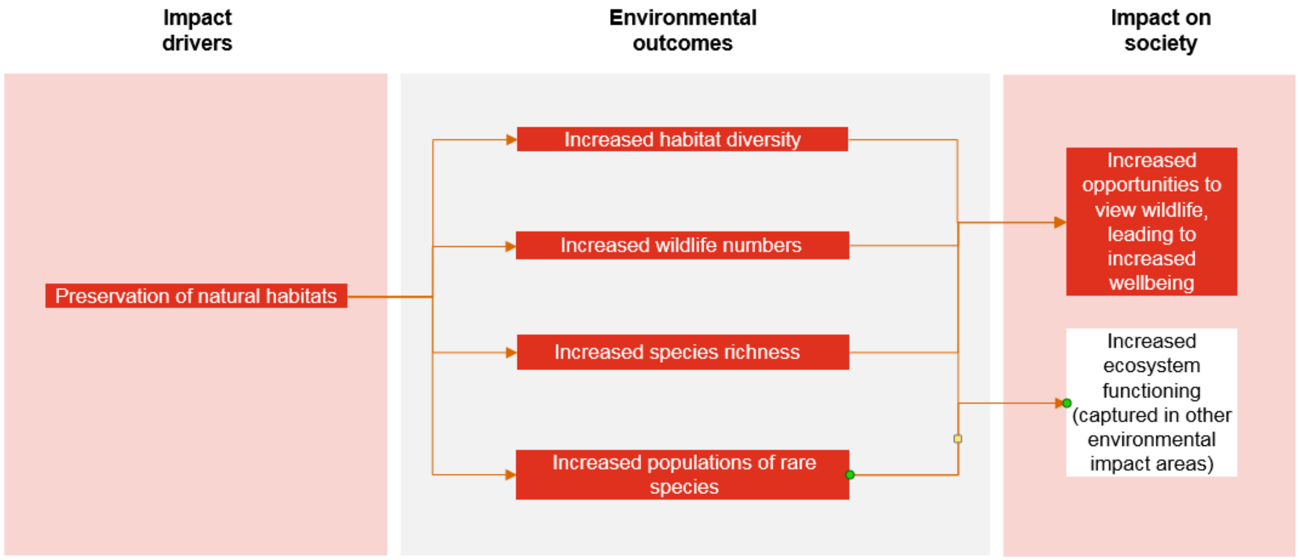
6.7.1. *The impact of ranching on habitats*

While almost all rural areas provide habitats for some species, conditions in modern conventional farming are often relatively hostile to nature. Practices such as the use of herbicides and pesticides, growing food crops in monoculture, and removal of trees and scrub all tend to limit the quality of habitats. Responsible land stewardship by ranchers provides a richer mix of habitats, including semi-natural environments that are becoming increasingly rare. These environments are often home to species of conservation concern.

TomKat manages its land according to principles aimed at generating efficient water, mineral, and solar energy cycling that in turn promotes healthy land and a more productive and resilient ranch. This includes supporting diverse plant, insect and wildlife communities and protecting sensitive areas by not allowing cattle to graze these areas. Of the 1800 acres at TomKat Ranch, only 776 acres are used as pasture. TomKat has chosen to protect the remaining area from the impacts of grazing. This supports five distinct ecological communities: coastal scrub, riparian, oak woodland, douglas-fir, and eucalyptus. In doing so, TomKat chooses to provide societal benefits in terms of habitat conservation over profit maximization.

6.7.2. *Impact pathway*

Figure 11: Habitat conservation impact pathway



6.7.3. *Approach to quantification and valuation*

As shown in the impact pathway, humans derive benefit from biodiversity through ecosystem services (Millennium Ecosystem Assessment 2005). Supporting, regulating and provisioning services are captured by other parts of the TIMM assessment – the conservation valuation concerns cultural ecosystem services - in this case, the wellbeing gained through experiencing diverse landscapes and wildlife, as well as the values that people express for knowing that important species and habitats are conserved, independent of personal experiences (‘existence’ or ‘bequest’ value).

In an economic valuation of the Conservation Reserve Program, wildlife viewing on retired farmland in the US was calculated as $10.02/acre (Feather et al. 1999). The value was inflated from 1999 prices to 2015 prices and applied to 921 acres. This represents the non-riparian area of TomKat Ranch that theoretically could be converted to pasture and grazed by cattle (slope gradient less than 70% (Mueggler 1965)), but TomKat has consciously chosen to preserve. (The value of riparian areas in terms of reducing sediment and nutrient loading into Honsinger Creek are valued under Sediment Control and Excess Nutrients impact areas, respectively.) It is assumed that a conventional rancher would maximize its profits by utilizing this land for grazing, and would therefore not generate the associated societal benefit.

6.7.4. *Limitations*

Our valuation is likely to be an underestimate as it does not account for the value of wildlife supported by TomKat’s large area of grazing grassland.

The valuation relies on a US-wide estimate of wildlife viewing value. More primary research on the value of wildlife viewing in TomKat's specific context would allow for the estimate to be refined. However, this would also limit the wider applicability of our estimates to other ranches.

Habitat conservation increases ecosystem function (Millennium Ecosystem Assessment 2005). This is only partially captured in the value of wildlife viewing and other impact areas valued in this assessment. Therefore our value of habitat conservation at TomKat Ranch is likely an underestimate of the full societal value.

7. Social impact valuation

7.1. Nutrition

7.1.1. *The impact of beef on nutrition*

Studies of grass-finished beef have shown numerous nutritional benefits compared to conventional grain-finished beef (Daley et al. 2010; Duckett et al. 2009). These nutritional benefits have been linked with various potential health benefits, as outlined in Table 28. The production of grass-finished beef therefore allows consumption of a nutritionally superior product that has positive impacts on consumer health, thereby generating a societal benefit.

Table 28: Nutritional benefits of grass-finished beef and potential health outcomes associated

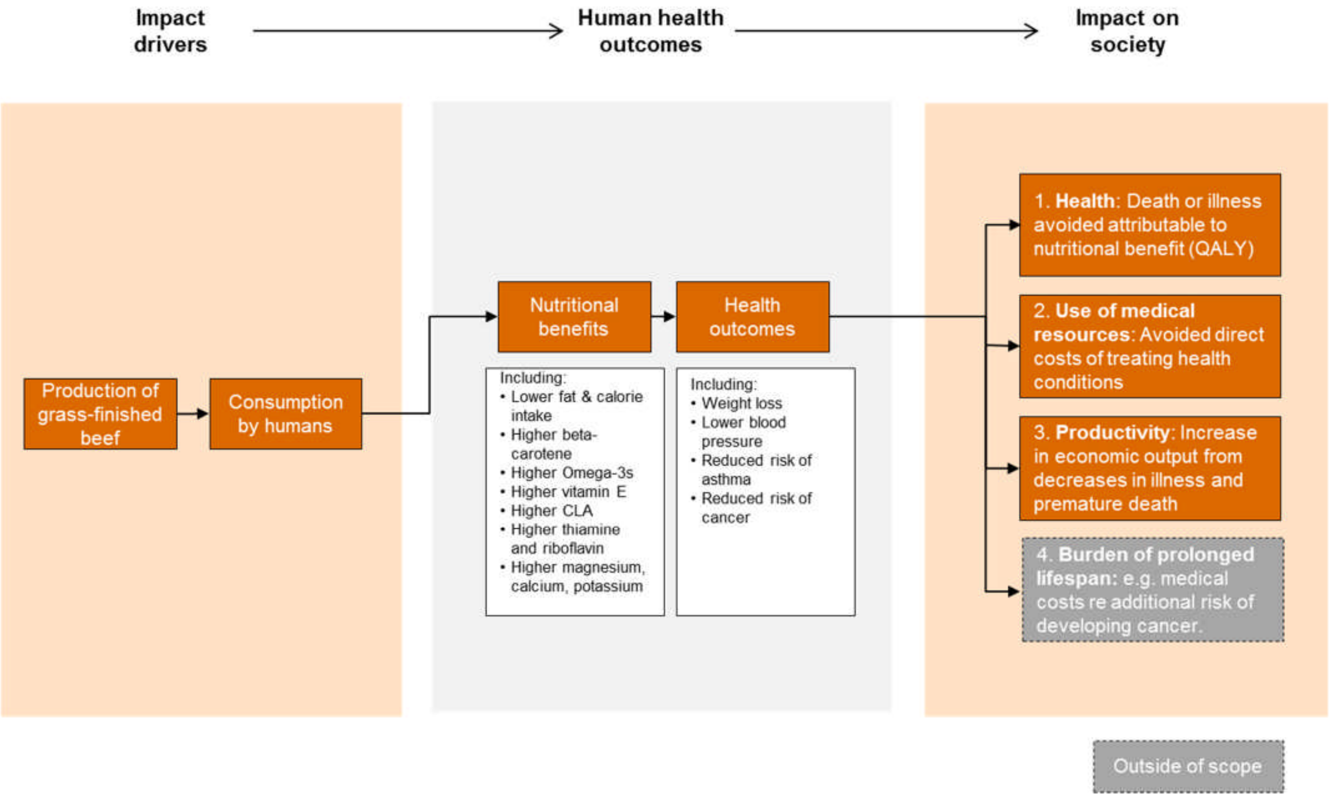
Nutritional benefit of grass-finished	Potential health outcomes
Lower in total fat and calories *104 fewer calories in 6-ounce grass-fed vs conventional (80% lean) ground beef (USDA, SR 21)*	By switching to lean grass-fed beef, it is estimated that the average person in the U.S. could reduce their calorie intake by up to 17,000 calories a year, which could equate to losing about six pounds.
Higher in beta-carotene *e.g., 7 fold increase in β-carotene levels for grass-fed beef (Daley et al., 2010)*	Carotenes (mainly β-carotene) are precursors of retinol (Vitamin A), a critical fat-soluble vitamin that is important for normal vision, bone growth, reproduction, cell division, and cell differentiation.
Higher in vitamin E (alpha-tocopherol) *e.g., 3-fold increase in a-tocopherol levels (Daley et al., 2010)*	Fat-soluble vitamin exists in eight different forms with powerful antioxidant activity, protecting cells against the effects of free radicals.
Higher in total omega-3s *e.g., omega-3 content of grass-fed beef enhanced by 60% (Abbott et al. 2004)*	Omega-3s reduce inflammation, lower the amount of serum cholesterol and triglycerides, prevent excess clotting and reduce the risk of cancer.
Higher in the B-vitamins thiamin and riboflavin *e.g. 100% more riboflavin found in pasture-raised beef compared to corn-fed (Duckett et al., 2009)*	Thiamine (B1) helps to maintain the body's energy supplies, coordinates the activity of nerves and muscles and supports proper heart function. Riboflavin (B2) helps protect cells from oxygen damage, supports cellular energy production and helps to maintain the body's supply of other B vitamins.
Higher in the minerals magnesium and potassium *e.g. 2% more magnesium, and 5% more potassium (Duckett et al., 2009)*	Magnesium helps to relax nerves and muscles, builds and strengthens bones and keeps the blood circulating smoothly. Potassium helps to maintain the proper electrolyte and acid-base balance in the body and helps lower the risk for high blood pressure.

7.1.2. *Impact pathway*

The impact pathway describes how production and subsequent consumption of grass-finished beef leads to nutritional benefits to the consumer, relative to the consumption of grain-finished beef, resulting in improved health outcomes. This ultimately leads to three types of impact on society:

- **Health:** Reduction in morbidity or mortality risk as a result of a healthier diet results in improved societal wellbeing.
- **Use of medical resources:** Avoided expenditure on medical resources for treating nutrition-related health conditions.
- **Productivity:** Increases in economic output from reductions in illness and premature death.

Figure 12: Nutrition impact pathway



7.1.3. *Approach to quantification*

The nutritional benefits of grass-finished compared to grain-finished were quantified based on the nutritional profile of raw ground beef from the USDA's National Nutrient Database for Standard Reference Release 27.[35]

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[35] Grass-finished: *13047, Beef, grass-fed, ground*, raw; grain-finished: *23508, USDA Commodity, beef, ground, bulk/coarse ground, frozen, raw*

7.1.4. ***Approach to valuation***

The valuation for nutrition captures the societal benefit of consuming grass-finished beef when compared to consuming an equivalent amount of grain-finished beef. The following steps were undertaken:

1. Identify which of the elements of nutrition are a concern in the average US diet. For example, there is generally no shortage of beta-carotene in US diets (National Institutes of Health 2013), so increased intake through grass-finished beef does not provide societal benefit. High calorie and high saturated fat diets contribute to obesity, which is a concern in the US, so lower intake of these through grass-finished beef should provide societal benefit.

2. For those nutritional elements that are of concern in the US diet, the next step was to identify studies that quantify the relationship between intake and human health outcomes i.e. 'dose-response' relationships.

    a. Where such studies could be identified, the value of improved health outcomes was estimated in terms of: (1) willingness to pay (WTP) for avoided illness and premature death, which takes into account loss of income; and (2) medical cost savings.

    b. Where suitable studies could not be identified, the change in health outcomes could not be quantified, and therefore could not be directly valued. In such cases the nutritional benefit was valued using the market value of supplements as proxies[36]. Due to market imperfections, particularly the lack of clear and transparent information to consumers on the health benefits of supplements for them personally, market values are not likely to provide a particularly good measure of the associated welfare benefits. However, given their low price relative to potential health benefits it's likely that they underestimate the overall welfare impact and we therefore include them as better than zero.

The results of these steps are summarized in Table 29. The total value per pound of beef is $1.63, the majority of which can be attributed to the significantly lower calorie and saturated fat content of grass-finished beef. The valuation approaches for these two aspects of nutrition are discussed in section 7.1.4.1.

Table 29: Approach to valuing nutritional benefits of grass-finished beef

Element of nutrition	Valuation approach	Size of benefit per lb of beef	Value of benefit per lb of beef
Energy	Medical cost savings and WTP for avoided morbidity and mortality	163 fewer calories (kcal)	$1.58
Saturated fat	Medical cost savings and WTP for avoided morbidity and mortality	6.7 fewer g of saturated fat	$0.04
Magnesium	Market value of supplements	9.0 mg more of magnesium	$0.004
Vitamin E	Market value of supplements	0.82 mg more of Vitamin E	$0.0002
Omega-3s	Market value of supplements	22.1 mg more Omega-3	$0.004
Potassium	Market value of supplements	195 mg more of potassium	$0.01
Beta-carotenes	No deficiency in US diet (National Institutes of Health 2013)	-	-
Thiamine	No deficiency in US diet (National Institutes of Health 2015b)	-	-

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[36] Based on first supplement listed on Amazon.com when sorted by best-selling, as at July 20th, 2015

Riboflavin	No deficiency in US diet (National Institutes of Health 2015a)	-	-
Total			**$1.63**

7.1.4.1. Valuation approach for energy and saturated fat

Dall et al. (2008) quantify the link between reduction in calorie and saturated fat intake and reduction in related co-morbidities. This is done by first modelling how a daily reduction in intake of 100 calories and 4 grams of saturated fat would change the profile of overweight and obese adults in the US, and then modelling the corresponding reduction in baseline disease prevalence rates due to reduction in obesity-related risk, based on data from the National Health and Nutrition Examination Survey (CDC & NCHS 2008). Dall et al. (2008) therefore quantify the dose-response relationship between reduction in calorie and saturated fat intake and reduction in number of cases of obesity-related diseases (see Table 3 in Dall et al. 2008).

WTP for avoided morbidity and mortality

To estimate WTP associated with averted obesity-related diseases, we first quantified avoided morbidity and mortality in terms of quality-adjusted life years (QALYs). QALYs are a commonly-used measure of disease burden, which take into account both the quality and quantity of life lived. Each case of illness averted is associated with the gain of a certain number of QALYs (Claxton et al. 2015). For example, each case of diabetes mellitus averted is associated with 2.7 QALYs over a lifetime. To take into account impacts over 100 years, we assume that two generations of US adults benefit from QALYs gained.

A monetary value is then attached to the total number of QALYs gained. The value of a QALY is derived from that developed by the UK Department of Health (Glover & Henderson 2010), which has been adjusted for the US by comparing UK and US estimates for WTP to avoid adverse health impacts (OECD 2012). The QALY value takes into account avoided loss of income due to disease/premature death, thereby capturing the productivity impact of improved health outcomes.

Finally, we identified the contribution of TomKat's beef to this societal benefit by taking into account the amount of TomKat beef produced annually, the reduction in calories consumed compared to the same weight of grass-finished beef, and the likelihood that TomKat beef would be consumed by an overweight or obese adult (62% based on proportion of overweight or obese Americans in 2007 (Dall et al. 2008)).

Medical cost savings

The annual cost savings per case of averted disease were also estimated by Dall et al. (2008) using the Medical Expenditure Panel Survey (MEPS 2004). We identified TomKat's contribution to reduced medical costs using the same approach as for QALYs.

7.1.5. ***Limitations***

Nutrition economics is a new branch of health economics. Therefore the research done in this field to date is limited. We did not identify any other studies that value specific nutritional elements of beef. We believe our approach offers new insight into consumption of nutritionally superior foods, but recognize it has limitations:

- The number of averted cases of disease and the estimate of medical costs were taken from a single study. This study has been peer-reviewed. We also cross-referenced estimates in the study (e.g. disease prevalence in the US) with those from reputable sources including World Health Organization and US Health Department. However, the valuation could benefit in future from more studies of this nature.

- We did not find sufficient research to quantify the dose-response relationship between nutritional elements other than calories and saturated fat. Therefore, the societal value of additional omega 3s, magnesium, thiamin and riboflavin are likely to be under-estimated.

- We do not value the impacts associated with increased burden due to prolonged lifespan. This is because there is insufficient research into what would happen to people who avoid an obesity-related disease (the counterfactual health outcomes).

- We assume obesity levels of the US adult population are constant into the future.

- The nutritional benefits are based on USDA nutritional information for generic grass-finished ground beef rather than analysis of TomKat's own beef.

- We exclude impact of hormone-free and antibiotic-free on human health. See section 7.2.5 and 7.2.6 for further detail.

7.2. Animal welfare

7.2.1. ***The impact of beef production on animal welfare***

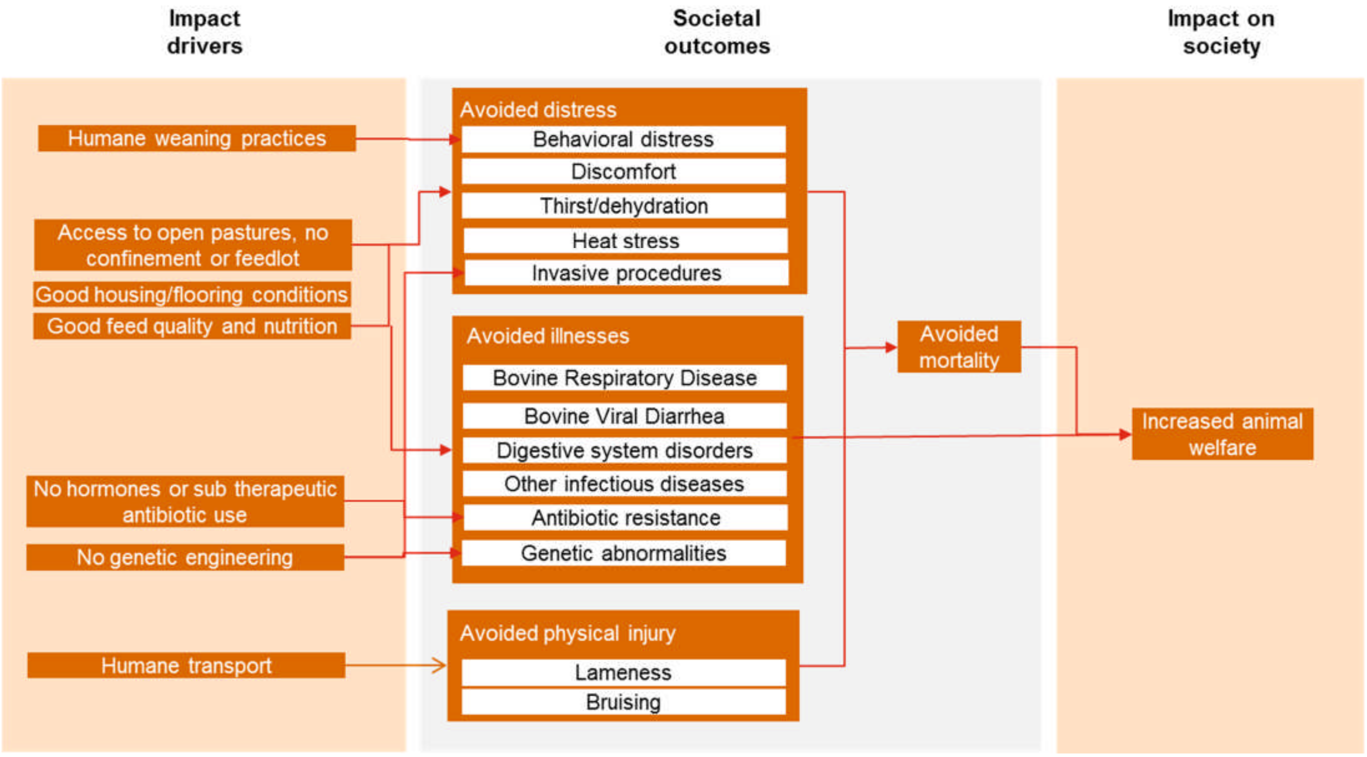
From an economic standpoint, the value of livestock is primarily derived from their ‘use’ or commercial value i.e. their contribution to the economic output of a farm/ranch. However, human preferences for ethics and fairness mean that farm animals can also have a ‘non-use’ value including an important and often significant value derived from knowing that the animals’ welfare is being looked after.

The World Organization for Animal Health defines animal welfare as “the state of the animal…how an animal is coping with the conditions in which it lives” (World Organisation for Animal Health 2015). By improving the animal’s living conditions, we can avoid animal distress, morbidity and/or mortality.

TomKat Ranch beef has American Grassfed Association (AGA) and Animal Welfare Approved (AWA) certifications. These attest that TomKat Ranch complies with requirements relating to how its animals are weaned, fed, housed, treated when ill, transported and slaughtered. These requirements lead to better animal welfare by avoiding situations that could lead to disease, dehydration, malnutrition, distress, lameness, bruising and digestive system disorders, among others. AGA certification requires that an animal receives no antibiotics or hormones; this is a key differentiator for TomKat beef from the counterfactual, and has separate impacts additional to animal welfare benefits – these are considered in sections 7.2.5 and 7.2.6.

7.2.2. ***Impact pathway***

Figure 13: Animal welfare impact pathway



7.2.3. *Approach to quantification and valuation*

We are aiming to value human wellbeing derived from improved animal welfare. While the commercial value of livestock can be inferred from the market price of meat, animal welfare tends to be a non-market good so its value is more difficult to estimate. Stated preference methods, including contingent valuation and choice modelling, are an established way of valuing non-market goods and services. They involve directly asking people to state their values for the good or service in question, for example by asking how much they would be willing to pay (WTP) for increased animal welfare because their own utility is directly affected or for altruistic concerns (Lagerkvist & Hess 2010).

The key advantage of stated preference methods is that, in theory, they give us a more complete estimation. However, historically many believe that the values derived are not reliable because they involve asking people hypothetical questions, rather than observing actual (market) behavior. In response to such criticisms, the methodologies have been significantly refined over the last 20 years to improve consistency and reliability and therefore enhance validity.

7.2.3.1. Selecting studies to include in the meta-analysis

We conducted a meta-analysis of peer-reviewed, published WTP studies. The meta-analysis included values for different cuts of beef (e.g. ground, steak).

We included only studies that produced WTP per unit of meat (rather than tax on weekly shop, annual tax) to reduce methodological inconsistencies. We used the percentage premium that consumers were willing to pay for higher welfare meat.

We included studies that examined one or more of the ‘humane animal practices’ on the impact pathway, and excluded studies/values only relating to taste or human nutrition. We excluded studies that assess WTP specifically for hormone-free or antibiotic-free because it is likely that respondents are taking into consideration his/her perceptions of the effects on human health of eating meat with hormones/antibiotics, rather than valuing the animal’s welfare per se.

Based on findings from Lagerkvist & Hess (2010), we included values not only from American studies but also from developed countries outside the US. However, Lagerkvist & Hess (2010) found that French, German and Danish consumers’ willingness to pay differed significantly from those of other developed countries, so studies from these countries were not included.

The eight studies were included are listed in Table 30.

Table 30: Studies used to calculate willingness to pay premium for higher animal welfare

Author	Year	Meat considered	Country	WTP % premium
Dickinson & Bailey	2002	Beef	USA (and Canada)	17%
Thilmany et al.	2003	Beef	USA	20%
Fields et al.	2006	Beef	USA	14%
Fields et al.	2006	Beef	USA	23%
Conner & Oppenheim	2008	Beef	USA	35%
Umberger et al.	2009	Beef	USA	11%
Napolitano et al.	2010	Beef	Italy	49%
Moran	2014	Beef	USA	36%

	Average	**26%**

The Lagerkvist & Hess (2010) meta-analysis of WTP for farm animal welfare did not review any Italian studies, so we cannot be sure that Italian consumers' WTP is representative of US consumers' WTP. If the Italian study is removed, average WTP premium falls to 22%. If studies are included that assess WTP specifically for hormone-free and/or antibiotic-free meat only (with no other animal welfare qualities), three extra studies are added to the meta-analysis and the premium increases to 30%.

Our willingness to pay estimate is sensitive to the choice of studies included, however, we are confident that the studies we have included are those which are most relevant to TomKat Ranch.

7.2.4. ***Limitations***

Some literature may not have been included including unpublished working papers and confidential reports. There may be publication bias in our sample; for example, Stanley (2005) found a bias towards reporting low WTP values in scientific publications due to 'referee/editorial skepticism' suggesting that our estimate may be conservative.

Methodological differences between studies will have introduced variations in the results. For example, Lagerkvist & Hess (2010) found that WTP values are lower when the animal welfare outcome is framed as a current or upcoming legal requirement, and no distinction is made for studies of this kind in our meta-analysis.

The meta-analysis does not include studies which look only at hormone and antibiotic-free aspects as WTP for these characteristics may reflect food safety fears about eating meat treated in these ways. However, this is likely to exclude some of the animal welfare aspects of hormone and antibiotic use, leading to potential underestimation of overall WTP.

7.2.5. ***Additional impacts of hormone-free meat***

Kuchler et al. (1989) reported that 95% of US cattle are implanted with growth hormones. Growth hormones used in cattle consist largely of natural and synthetic androgens, progesterone and oestrogens, and are reported to improve weight gain by 5 to 20 percent, feed efficiency by 5 to 12 percent, and lean meat growth by 15 to 25 percent (Kenney & Fallert 1989). However, there have been fears among consumers and regulatory entities over the safety of these substances and their metabolites. Human consumption of meat which contains elevated hormone levels and environmental contamination by livestock excretions are the key areas of concern.

A 1998 opinion poll found that 54 percent of EU consumers felt that the absence of any hormones in food is necessary for the food to be considered safe (INRA Europe 1998). In the US, 50 percent of consumers said hormones were a serious hazard when specifically asked (Lusk et al. 2003).

7.2.5.1. Human health

The US Food and Drug Administration and Joint Food and Agricultural Organisation/World Health Organisation expert committee on food additives (JECFA) concluded in 1988 that the meat from hormone-treated animals was safe for human consumption. However, research in the European Journal of Endocrinology (Andersson & Skakkebaek 1999) argues that this judgement was based on "uncertain assumptions and inadequate scientific data".

The European Community banned all US beef in 1989 due to public pressure over health fears related to the presence of hormone implants. The EU took a precautionary approach and has been unable to conclusively prove in the intervening years whether there are any negative health effects. A European Commission review of available evidence in 1999 (European Commission 1999), and a review based on new evidence in 2002 (European Commission 2002), found that health impacts could reasonably be expected from eating hormone-treated meat, but that the body of evidence was not yet big enough to determine for sure the level of risk. They determined that risks are highest for those with lowest body hormone levels, e.g. prepubertal children. Genotoxic effects have been found during tests on lab animals for some of the hormones.[37]

A more recent review of the available evidence (Aksglaede et al. 2006) concluded that the risks to children still have not been properly assessed, and the high sensitivity of children to hormones puts them at particular risk of any endocrine disruption effects.

7.2.5.2. Environmental damage

There are concerns about the fate in the environment of exogenous hormones given to cattle after excretion by the animal. Studies have found between 8% and 65% of a hormone dose to be traceable in animal manure and urine. If these hormones persist in the environment, they will likely enter watercourses, where some hormones (e.g. oestradiol-17β) have been shown to have adverse effects on the reproductive systems of fish and amphibians (Lange et al. 2002).

Lange et al. (2002) reviewed the evidence for the environmental impact that these hormones may have. They estimated that excreted exogenous hormones add an additional 0.2% to estrogens excreted naturally by livestock and 20% to androgens excreted naturally by livestock in the US. Synthetic hormones are designed to be more stable and bioactive than natural hormones so that they produce more reliable growth effects, but this may contribute to their persistence in food products and the environment. Lange et al concluded that while there are potential routes for hormones to have an environmental impact, especially in disrupting the hormonal systems of aquatic animals, insufficient research has been carried out to confirm or quantify the risk.

A more recent study by (Kolok & Sellin 2008) shows that while hormones have been found to persist in the environment, and certain growth hormones have been found to have endocrine disruption effects in aquatic organisms, the studies needed to prove a causative link have not yet been done.

7.2.5.3. Conclusion

We are aware of the potential health and environmental impacts of hormone use in livestock, which is why TomKat does not use any hormones in its production system. However, the current lack of substantive scientific evidence means these impacts cannot be confirmed or quantified, making it difficult to attach a monetary value to them. We have therefore excluded impacts of hormones on health and environment from the analysis, potentially under-estimating the societal benefits of beef produced at TomKat Ranch.

7.2.6. ***Additional impacts of antibiotic-free meat***

Sub-therapeutic levels of antibiotics are commonly fed to livestock in the US with the aim of producing a number of beneficial outcomes, including; prevention and treatment of animal diseases, faster growth rates, potential reduction of methane production in the rumen and protection of humans against food-borne illnesses (Hao et al. 2014).

Animal diseases spread more rapidly in intensive animal production (Gilchrist et al. 2007), so antibiotics are used more widely in these situations. TomKat Ranch animals do not receive antibiotics in their feed.

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[37] In 2012 the EU loosened restrictions, allowing import of a quota of ‘high quality’ (only hormone-free) US beef.

7.2.6.1. The resistance issue

Agriculture is the largest user of antimicrobials worldwide, utilising drugs of every important clinical class (Silbergeld et al. 2008). Bacterial exposure to sub-therapeutic antimicrobials selects for resistance to the antibiotic amongst the bacterial population, resulting in bacteria which cannot be killed using certain antibiotics (e.g. methicillin resistant Staphylococcus aureus (MRSA)). Humans are exposed to these antibiotic-resistant pathogens when they consume animal products as well as through widespread release into the environment (e.g. airborne transport downwind from cattle farms (McEachran et al. 2015)). Treating antibiotic-resistant infections is a growing problem and poses a serious threat to public health (European Food Safety Authority 2015).

It is currently unclear what share of responsibility for antibiotic resistance might be attributable to animal agriculture, as opposed to misuse of antibiotics in humans. Even the scale of antibiotic use in the US is highly uncertain, with estimates for the proportion of all antibiotics which are used on animals varying from 40% to 87% (Gilchrist et al. 2007).

Silbergeld et al. (2008) reviewed the current state of knowledge of this issue and found that:

- Agricultural antimicrobial use results in the exposure of farmers, farm workers, rural communities, and the general public to antimicrobial resistant pathogens, as well as contamination of air, water, and soils near food-animal production sites.

- For public health, the most significant impact of agricultural antimicrobial use is the expansion of resistant bacteria in the livestock population, because the resistant genes can be transferred widely among microbial communities.

- Disposal of animal waste is a major route of environmental contamination by antimicrobials and resistance determinants.

- Farmers and farm workers are at significantly increased risk of infection by antimicrobial-resistant bacteria; they may serve as entry points for the general community and transfers into healthcare settings.

- Reducing or banning agricultural antimicrobial use can reduce risks of antimicrobial resistance in the food supply.

7.2.6.2. Policy responses

The European Union banned the use of antibiotics for non-therapeutic purposes in 2006 (Sorensen et al. 2014), while the US continues to allow antibiotics to be used on a large scale. Sorensen et al found that the response to the threat in the US had been lacking, with very little investment in collecting data relating to antibiotic-resistant infections. As a result, there is not enough information for scientifically-informed policy decisions.

7.2.6.3. Conclusion

We are aware of the negative impact of antibiotic use in agriculture on public health, but there are not yet enough data about the scale of the issue for us to be able to place a value on TomKat's restriction on antibiotic use. We are therefore potentially underestimating the societal benefits of beef produced at TomKat Ranch on human health.

8. Research gaps

Research gap	Rationale	Specific areas of focus	Priority
Systematic research on the rate and duration of **soil carbon sequestration**	Could have a substantial impact on the GHG footprint of beef production, but typically not included in lifecycle assessments Current literature on soil sequestration relating to intensive rotational grazing is particularly weak and inconsistent Soil C sequestration is an important driver of net GHGs in TomKat's total impact	Systems (intensive rotational grazing, conventional grazing, range lands, coastal scrub) Time scales (particularly medium- and long-term) Locations (different climates and geographies) Sward composition (annual, perennial, scrub, legume etc.)	High
Effects of alternative ranching systems (particularly **intensive rotational grazing)**	Intensive rotational grazing is a key differentiator from the counterfactual Large body of anecdotal evidence is not currently backed up by consensus in peer-reviewed studies Forage productivity and soil characteristics determine the carrying capacity of the land and the profitability of the business Better evidence needed to persuade policy-makers to act and conventional ranchers to change	Soil physical characteristics / structure beyond carbon sequestration e.g. bulk density, water holding capacity Considering: • Time scales (short-, medium-, and long-term) • Locations (different climatic and geographic criteria) • Sward composition (annual, perennial, scrub, legume etc.) Focusing on: • Forage productivity (annual and seasonal yield)	High
Effects of **compost application**	Could have a substantial impact on carbon sequestration and emissions Evidence is encouraging but currently limited Effects are dependent on site-specific conditions	Considering: • Time scales (particularly medium- and long-term) • Locations (different climates and geographies) • Sward composition (annual, perennial, scrub, legume etc.) • Systems (intensive rotational grazing, conventional grazing, crop lands, range lands, coastal scrub) Focusing on:	High

	Important for making management decisions	• GHGs (carbon sequestration and effect on nitrous oxide balance) • Forage productivity • Nitrate leaching	
Optimal **stocking density**	Relationship between stocking density and factors such as carbon sequestration not well researched Little understanding of the context/geographical characteristics Important to understand for making management decisions that maximize benefits	Considering: • Number of animals, as well as intensity and duration of grazing • Time scales (short-, medium-, and long-term) • Locations (different climatic and geographic criteria) • Sward composition (annual, perennial, scrub, legume etc.) Focusing on: • Carbon sequestration • Methane emitted • Forage productivity	High
Effects of additional **conservation efforts**	To allow assessment of relative importance of different conservation actions and assist with prioritization To allow more accurate and representative valuation of conservation	Considering: • Time scales (short-, medium-, and long-term) • Locations (different climatic and geographic criteria) • Conservation activities (riparian area extension, integration of coastal scrub) Focusing on: • Forage productivity (annual and seasonal yield) • GHGs (carbon sequestration and nitrous oxide) • Excess nutrients (nitrate leaching) • Valuing biodiversity (holistic way to measure, conservation credits)	Medium
Ability of intensive rotational grazing system to **withstand shocks**	Extreme weather events are likely to increase in the future due to climate change If intensive rotational grazing is more resilient than conventional system, this	Considering extreme weather events: • Precipitation – drought / flood / rapid variation • Temperature – maximum / minimum / rapid variation	Medium

	could be convincing reason for others to change	Focusing on: • Forage productivity (annual and seasonal yield) • GHGs (carbon sequestration and nitrous oxide) • Excess nutrients (nitrate leaching)	
Activities required to increase or **maintain soil carbon stocks** post 2050	Informing management decisions to increase period of sequestration	Minimum stocking density required Impacts of return to natural sward composition, considering: • Time scales (short-, medium-, and long-term) • Locations (different climatic and geographic criteria)	**Medium**
Ability of **IFSM / alternative models'** to accurately predict **forage productivity** from intensive rotational grazing	Could have a significant effect on estimates of ranch level productivity	Effect of fog Effect of microbial biodiversity	Medium
Confirming **IFSM / alternative models' sensitivity to bulk density**	Could have a significant effect on forage productivity and nitrous oxide production		Medium
Ability of **IFSM / alternative models** to model **multiple species** of animals on ranch	Could have a significant effect on estimates of ranch level profitability		Low
Ability of **IFSM / alternative models** to quantify the amount of **soil detached** in watercourse	Could have a significant effect on the quantity of excess nutrients		Low
Volume of **methane** produced by cows	Informing management decisions to reduce GHG impacts	Effect of diets (corn, grass, barley fodder etc.) Activities to reduce (additional weight in rumen) Amount digested/sequestered by bacteria	Low
Effects of **sub-therapeutic antibiotic** use	Key differentiator from the counterfactual Lack of consensus in the literature	Focusing on antibiotic-resistant strains of bacteria Animal health when directly consumed or through excess in the water course Human health when consumed through meat intake or excess in the water course	**Low**

Effects of **hormone** use	Key differentiator from the counterfactual	Focusing on reproductive health Animal health when directly consumed or through excess in the water course Human health when consumed through meat intake or excess in the water course	Low
Downstream effects of **E. coli** on human health	Potential to be a differentiator from the counterfactual		Low
Effects of **animal stress** on nutritional profile of meat	Animal welfare is a key differentiator from the counterfactual		Low
Health benefits of additional **vitamins and minerals**	Nutrition is a significant benefit compared to the counterfactual	Magnesium, Vitamin E, Omega-3s, and Potassium	Low
Effect of intensive rotational grazing on **taste**	Additional consumer preference factor not considered Taste is a key factor for consumer choice		Low
Effects of **glyphosate** use on human health	Herbicide use in corn is a key differentiator for the counterfactual		Low

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Appendices

A.1. Description of IFSM

The Integrated Farm System Model (IFSM) simulates a cradle-to-farm gate production system, including crop and pasture production, crop harvest, feed storage, grazing, feeding, and manure handling. It is an integrated model that is able to represent the major interactions between various biological and physical processes on a beef farm. It has been developed over 30 years by Dr Al Rotz, an agricultural engineer at the USDA.

How it works: IFSM uses computer simulation to model a user-specified farm production system on a process level (Rotz et al. 2014). Processes modelled include crop growth, manure handling, feed allocation and animal response, and nutrient flows. Underlying models on which IFSM relies include: GRASIM (grass growth), DAYCENT (nutrient flows), MUSLE (sediment erosion), Cornell Net Carbohydrate and Protein System (cattle energy and protein requirements). IFSM draws on over 200 academic references.

Inputs: Input data are specified in three parameter files. Most of the parameters in these can be modified using the program's user interface. This offers a high degree of user-customization.

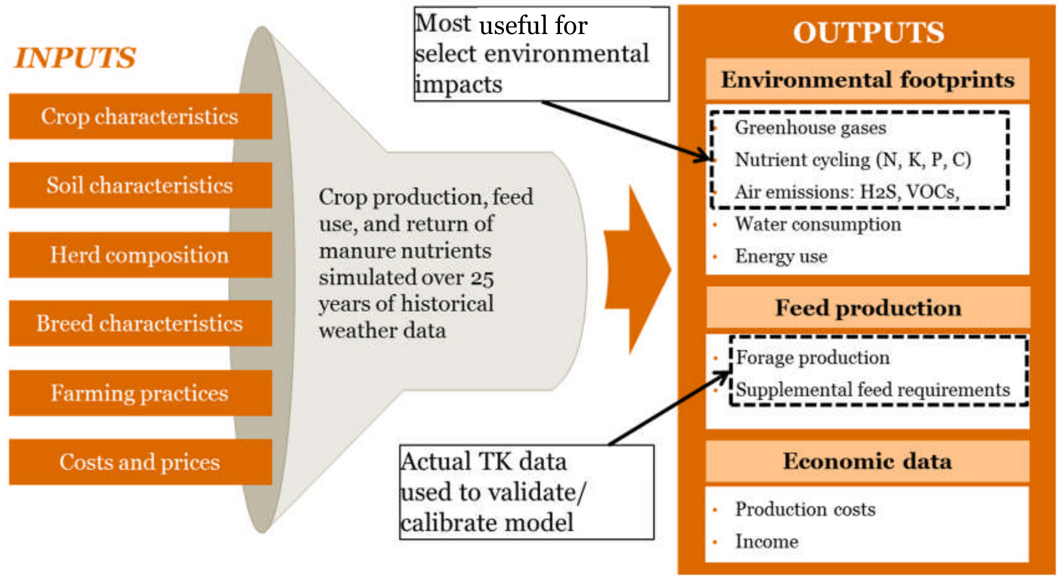
(1) The farm file includes details on soil and crop characteristics, animal breed characteristics, farming practices (e.g. tillage, harvesting, machinery operation, manure handling), and costs;

(2) The weather file contains daily weather information for a particular location. The required weather data are: precipitation, maximum/minimum temperature, solar radiation, and average wind speed; and

(3) The machinery file includes details on each machine used on the farm, such as weight, engine type, and usage.

Outputs: Outputs modelled on an annual basis include crop yields, feeds produced, manure produced, water balance, environmental impacts (e.g. carbon balance, nutrient balances, water consumption) per unit of final shrunk body weight (FSBW) sold i.e. 96% of live body weight. IFSM also models production costs and expected returns. We do not anticipate using these outputs from the model.

For further information on IFSM, Rotz (2007) provides a summary, and Rotz et al. (2014) provide a comprehensive description.



A.2. GHG modelling requirements by driver of emissions

Key

Modelled using IFSM
Estimated using alternative approach

Upstream		***On-farm***		***Downstream***	
Driver of emissions	**GHGs**	**Driver of emissions**	**GHGs**	**Driver of emissions**	**GHGs**
Purchased feed production	Sense-checked IFSM estimate of purchased feed against actual (345,600 lbs of hay in 2014/15)	Cattle (enteric fermentation)	Modelling required as primary measurements technically challenging and expensive; static secondary estimates unlikely to be accurate	Transportation to/from abattoir	Not within scope of IFSM, so use actual distance/fuel estimates and lifecycle assessment factors from the WRI Transport Tool
Feed transportation	Use same assumptions as Stackhouse-Lawson et al. 2012 for purchased hay and grain transportation	Animal transportation (between leased properties)	Not included within IFSM; added based on actual fuel data	Slaughtering and packaging process	Based on LCA data; no difference between our system and counterfactual
Fertilizer and pesticide production	Based on amount of purchased feed purchased as estimated by IFSM; production factors from LCA data	Pasture/cropland emissions	Modelling required (see above comment on cattle). Background N2O from pasture (e.g. nitrous oxide produced even when no cattle are present) removed to allow fair comparison. We only take into account the additional effect of manure deposits on pasture.	Transportation to customers	Not within scope of IFSM, use actual distance estimates. For counterfactual, estimate based on literature (King, et al., 2010)
Seed production	Based on typical seeding factor of 0.9kg seed/t DM, as estimated by IFSM. Likely to be immaterial overall	Manure	Modelling required (see above comment on cattle)	Fuel and electricity in storage and cooking	Based on LCA data; no difference between our system and counterfactual
Fuel and electricity production	Quantify using actual fuel & electricity data; use IFSM's emissions factors for consistency with counterfactual	Fuel and electricity consumption	Use actual estimate of fuel and electricity use; use IFSM's emission factors for consistency with counterfactual	Packaging disposal	Based on LCA data; no difference between our system and counterfactual

Machinery production	Use emissions factor in IFSM (3.54 kg CO2e/kg spread over lifetime of machinery) but quantify TomKat's actual machinery weight	Soil carbon sequestration	Not included in IFSM; see Section 4.		
Hormone production	For counterfactual only. Used LCA data				

A.3. Water consumption modelling requirements by driver of resource use

Key

To be modelled using IFSM
To be estimated using alternative approach
Source of emissions excluded from scope of the assessment

Upstream			*On-farm*			*Downstream*		
Driver of resource use	**Volume**	**Source**	**Driver of resource use**	**Volume**	**Source**	**Driver of resource use**	**Volume**	**Source**
Purchased feed production	Modelling required because primary measurements are not available from suppliers; IFSM volume sense-checked against literature	Assumptions based on iGIS mapping and literature review	Cattle drinking water	Modelling required because primary measurements are technically challenging and expensive; secondary estimates are unlikely to be accurate	Assumptions based on information provided by CEMAR	Transportation to/from abattoir	Not within scope of IFSM, so use actual distance/fuel estimates	Assumptions based on information provided in the literature
Feed transportation	Not within scope of IFSM	Assumptions based on information provided in the literature	Animal transportation (between leased properties)	Not included within IFSM; will be added based on actual fuel data	Assumptions based on information provided in the literature	Slaughtering process	No difference between and counterfactual	N/A
Fertilizer and pesticide production	Water used in the production of fertilizer and pesticides is considered immaterial	N/A	Fuel and electricity consumption	Quantify using actual fuel & electricity data; use emissions resource use factors	Assumptions based on information provided in the literature	Transportation to customers	Not within scope of IFSM, use actual distance/fuel estimates	N/A

Seed production	Based on an average water footprint of 2.0 Mg/kg of seed production. Likely to be immaterial overall	Assumptions based on information provided in the literature	Operational water	Primary information provided by CEMAR	Primary information provided by CEMAR	Fuel and electricity in cooking	No difference between our production system and counterfactual	N/A
Fuel and electricity production	Quantify using actual fuel & electricity data; use emissions resource use factors	Assumptions based on information provided in the literature	Soil water storage	Not included in IFSM; see separate Section 4.	See Section 4.			
Machinery production and repair	Water used in machinery production and repair is considered immaterial	N/A						
Antibiotic and hormone production	Not included within IFSM scope; impacts likely to be immaterial	N/A						

A.4. Excess nutrient requirements by driver of emissions

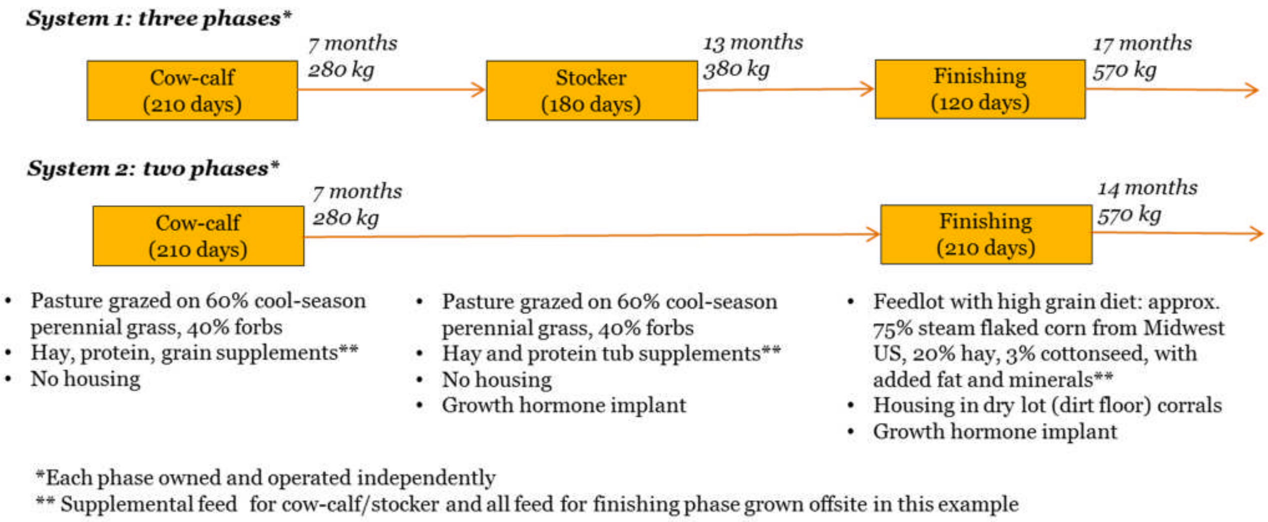
Key

To be modelled using IFSM
To be estimated using alternative approach
Source of emissions excluded from scope of the assessment

Upstream			*On-farm*			*Downstream*		
Driver of discharges	**Nutrients**	**Heavy Metals and Toxins**	**Driver of discharges**	**Nutrients**	**Heavy Metals and Toxins**	**Driver of discharges**	**Nutrients**	**Heavy Metals and Toxins**
Purchased feed production	Modelling required because primary measurements are not available from suppliers; IFSM volume sense-checked against literature	Values based on literature review of active ingredient runoff from key pesticides and fertilizers	Cattle (waste)	Modelling required because primary measurements are technically challenging and expensive; secondary estimates are unlikely to be accurate	Values based on literature review of active ingredient runoff from cattle	Transportation to/from abattoir	Impacts likely to be immaterial	Impacts likely to be immaterial
Feed transportation	Impacts likely to be immaterial	Impacts likely to be immaterial	Animal transportation (between leased properties)	Impacts likely to be immaterial	Impacts likely to be immaterial	Slaughtering process	No difference between our production system and counterfactual	No difference between our production system and counterfactual
Fertilizer and pesticide production	Impacts likely to be immaterial in developed country due to discharge regulations	Impacts likely to be immaterial in developed country due to discharge regulations	Fuel and electricity consumption	Impacts likely to be immaterial	Impacts likely to be immaterial	Transportation to customers	Impacts likely to be immaterial	Impacts likely to be immaterial

Seed production	Impacts likely to be immaterial in developed country due to discharge regulations	Impacts likely to be immaterial in developed country due to discharge regulations	Operational discharge	Impacts likely to be immaterial	Impacts likely to be immaterial	Fuel and electricity in cooking	No difference between our production system and counterfactual	No difference between our production system and counterfactual
Fuel and electricity production	Impacts likely to be immaterial	Quantify using actual fuel & electricity data; use discharge factors	Soil holding capacity	Not included in IFSM; see Section 4.	Not included in IFSM; see Section 4.			
Machinery production and repair	Impacts are difficult to quantify and likely to be immaterial	Impacts are difficult to quantify and likely to be immaterial						
Antibiotic and hormone production	Impacts likely to be immaterial in developed country due to discharge regulations	Impacts likely to be immaterial in developed country due to discharge regulations						

A.5. Overview of Angus beef production systems described by Stackhouse-Lawson et al. (2012)



- Pasture grazed on 60% cool-season perennial grass, 40% forbs
- Hay, protein, grain supplements**
- No housing

- Pasture grazed on 60% cool-season perennial grass, 40% forbs
- Hay and protein tub supplements**
- No housing
- Growth hormone implant

- Feedlot with high grain diet: approx. 75% steam flaked corn from Midwest US, 20% hay, 3% cottonseed, with added fat and minerals**
- Housing in dry lot (dirt floor) corrals
- Growth hormone implant

*Each phase owned and operated independently
** Supplemental feed for cow-calf/stocker and all feed for finishing phase grown offsite in this example

Source: Stackhouse-Lawson et al. (2012)

A.6. Detailed characteristics of beef production system described by Stackhouse-Lawson et al. (2012)

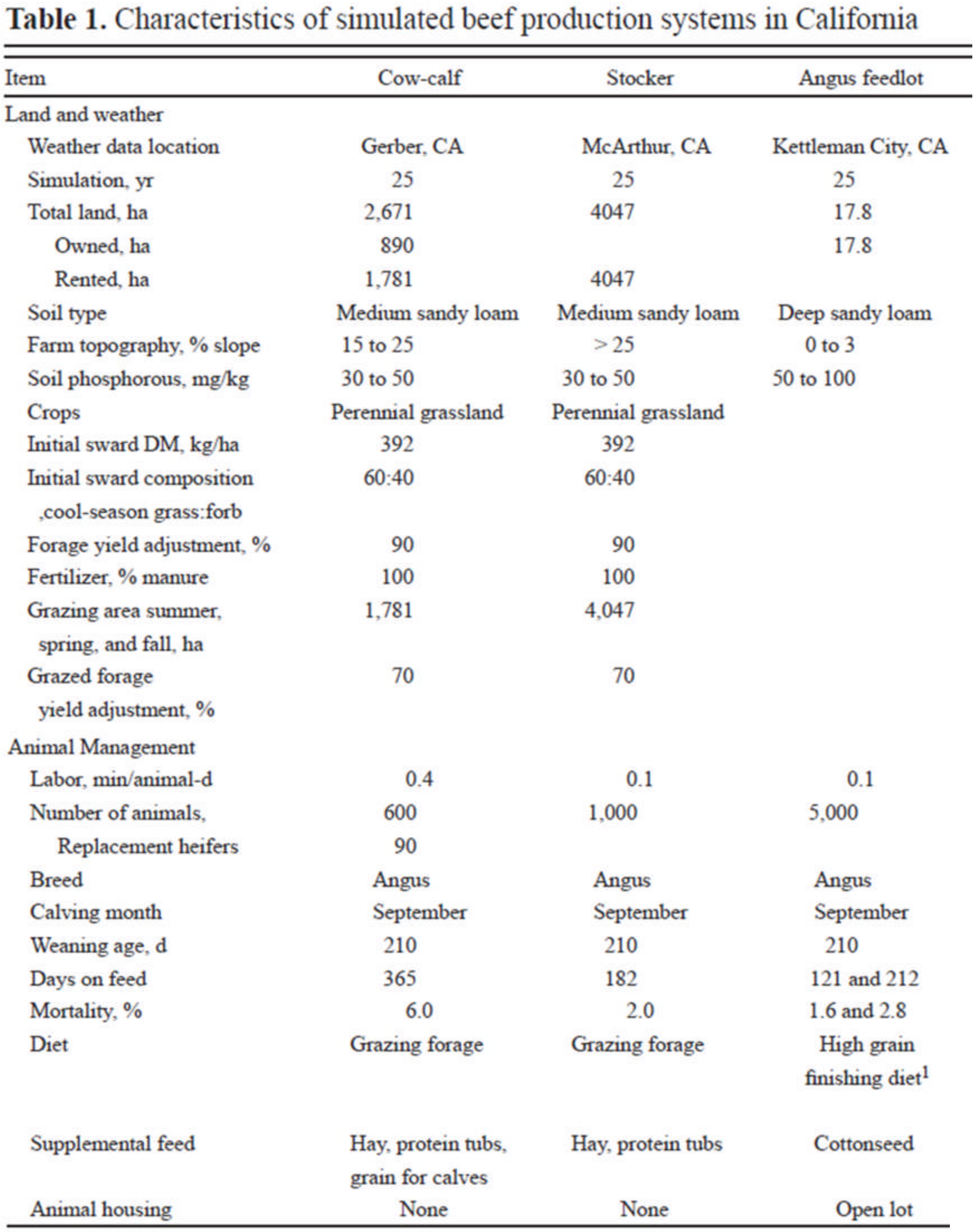
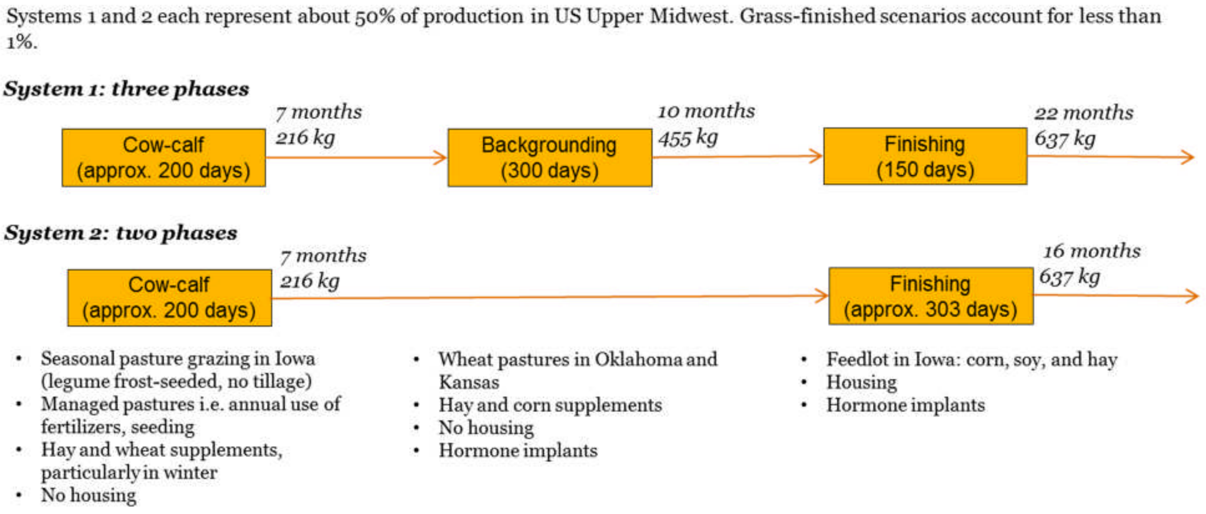


Table 1. Characteristics of simulated beef production systems in California

Item	Cow-calf	Stocker	Angus feedlot
Land and weather			
Weather data location	Gerber, CA	McArthur, CA	Kettleman City, CA
Simulation, yr	25	25	25
Total land, ha	2,671	4047	17.8
Owned, ha	890		17.8
Rented, ha	1,781	4047	
Soil type	Medium sandy loam	Medium sandy loam	Deep sandy loam
Farm topography, % slope	15 to 25	> 25	0 to 3
Soil phosphorous, mg/kg	30 to 50	30 to 50	50 to 100
Crops	Perennial grassland	Perennial grassland	
Initial sward DM, kg/ha	392	392	
Initial sward composition ,cool-season grass:forb	60:40	60:40	
Forage yield adjustment, %	90	90	
Fertilizer, % manure	100	100	
Grazing area summer, spring, and fall, ha	1,781	4,047	
Grazed forage yield adjustment, %	70	70	
Animal Management			
Labor, min/animal-d	0.4	0.1	0.1
Number of animals,	600	1,000	5,000
Replacement heifers	90		
Breed	Angus	Angus	Angus
Calving month	September	September	September
Weaning age, d	210	210	210
Days on feed	365	182	121 and 212
Mortality, %	6.0	2.0	1.6 and 2.8
Diet	Grazing forage	Grazing forage	High grain finishing diet[1]
Supplemental feed	Hay, protein tubs, grain for calves	Hay, protein tubs	Cottonseed
Animal housing	None	None	Open lot

Source: Stackhouse-Lawson et al. (2012)

A.7. Overview of beef production system described by Pelletier et al. (2010)



Systems 1 and 2 each represent about 50% of production in US Upper Midwest. Grass-finished scenarios account for less than 1%.

- Seasonal pasture grazing in Iowa (legume frost-seeded, no tillage)
- Managed pastures i.e. annual use of fertilizers, seeding
- Hay and wheat supplements, particularly in winter
- No housing

- Wheat pastures in Oklahoma and Kansas
- Hay and corn supplements
- No housing
- Hormone implants

- Feedlot in Iowa: corn, soy, and hay
- Housing
- Hormone implants

Source: Pelletier et al. (2010)

A.8. Indicative categorization of intensive rotational grazing research by environmental outcome[38]

🟢 Study showing a beneficial effect
⚪ Study showing no significant effect
🔴 Study showing a negative effect

		Reference	Findings
Forage composition	🟢	Earl & Jones 1996	Palatable grasses increased in multipaddock grazing
	🟢	Heitschmidt et al 1987b	Crude protein and organic matter digestibility higher with rotational grazing
	🟢	Henneman et al 2014	Perennial grasses increased over time with intensive rotational grazing (at TomKat Ranch)
	🟢	Stahlheber & D'Antonio 2013	Native grass cover generally increased with grazing, although with high variation among studies (meta-analysis - rotational grazing not studied)
	🟢	Teague et al 2011	Desirable high seral grasses dominant in multipaddock grazing
	🟢	Teague et al 2004	Rotational grazing had greater increases in perennial basal area when weather is favourable, smaller decreases in drought conditions
	⚪	Bartolome 2004	Grazing removal increased perennial grass abundance (rotational grazing not studied)
	⚪	Biondini & Manske 1996	No differences found in species composition between rotational and season-long grazing
	⚪	Hall et al 2014	No consistent differences in plant species composition between grazing methods
	⚪	Manley et al 1997	Effects of grazing strategy on vegetation were insignificant
	⚪	Martin & Severson 1988	Perennial grass density with the Santa Rita grazing system was not different from continuous grazing
Water holding capacity	🟢	Beukes & Cowling 2003	Grazing leads to increased stability, infiltration, and a higher water content due to a more active soil biota
	🟢	Teague et al 2013	Multi-paddock grazing increases perennial basal, represented by higher fungal to bacterial ratio which indicates superior water holding capacity and nutrient availability
	🟢	Teague et al 2011	Water-holding capacity is higher with multi-paddock than light or heavy continuous, based on its positive relationship with soil C
	🟢	Weber & Gokhale 2010	Volumetric water content is significantly higher for intensive rotational grazing than rest-rotation (low density for long periods of time)
	🟢	Mapfumo et al 2000	Change in water holding capacity for medium and light grazing, was positive and significantly greater than that for the heavy grazing.

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[38] The scientific literature dedicated to specifically and quantitatively assessing the outcomes associated with 'intensive rotational grazing', following methods that align closely with those practiced at TomKat Ranch, is extremely limited. A related issue when reviewing the literature is that precise descriptions of the management system actually being assessed are frequently lacking. For this reason it was necessary to extend our literature review to ranching systems that appear sufficiently similar to offer insights into the outcomes we might expect from intensive rotational grazing (e.g. rotational grazing, multi-paddock grazing, low frequency high intensity grazing). However, as discussed in section 4, this should be borne in mind when drawing conclusions on the basis of the existing literature.

Topsoil organic carbon	🟢	Teague at al 2011	Soil organic matter was significantly higher under multi-paddock grazing than heavy continuous or light continuous grazing.
	🟢	Sanjari et al 2008	Up to 626 kgC/ha/year more soil organic carbon in topsoil under time-controlled grazing compared to continuous grazing, but result not statistically significant (p = 0.16).
	⚪	Manley et al. 1995	Found no significant differences in soil C in top 91cm of soil between continuous and rotationally deferred/short-duration grazing.
	🔴	Beukes & Cowling 2003	High-intensity, low-frequency grazing significantly lowered the amount of organic carbon in the topsoil.
Bulk density	🟢	Sanjari et al 2008	A significant increase in bulk density was found under continuous grazing but not under time-controlled grazing.
	🟢	Teague et al 2011	Results showed bulk density was lower under multi-paddock grazing than heavy continuous or light continuous grazing, but not at a statistically significant level (p>0.05).
	⚪	Abdel-Magid et al 1987	No significant differences in soil bulk densities between continuous grazing, rotationally deferred, and short duration grazing.
Bare ground	🟢	Manley et al 1997	Significantly more bare ground under season-long heavy grazing than for short duration grazing and rotationally deferred grazing in certain years.
	🟢	Teague et al 2011	Bare ground was significantly higher under heavy continuous grazing than under multi-paddock grazing.
	🔴	Pluhar et al 1987	Rotational grazing significantly increased bare ground and decreased vegetation cover compared to continuous grazing at moderate stocking rates.
Soil nitrogen	🟢	Biondini & Manske 1996	Net N mineralization increased by 460% under rotational grazing over two years, and did not show a clear trend with continuous grazing or no grazing.
	⚪	Manley et al. 1995	Higher soil N in surface 30cm of grazed pasture compared to un-grazed. However, found no significant differences in soil N between continuous and rotationally deferred/short-duration grazing.
	🔴	Sanjari et al 2008	Sharp decrease in nitrate levels at rotationally grazed site, where nitrate levels increased at one of two continuously grazed sites.
	🔴	Wilms et al 1990	Short duration grazing reduced soil organic nitrogen compared to ungrazed land
Run-off/erosion	🟢	Rotz et al 2009	Converting cropland to perennial grassland through rotational grazing reduces erosion by 24% (as predicted by IFSM)
	⚪	Beukes & Cowling 2003	Soil subject to high-intensity, low-frequency grazing had improved water infiltration capacity compared to ungrazed soil when rain was simulated on disturbed soils. However, no significant difference in infiltration when rain was simulated on sealed soils (which is closer to field conditions most of the time). No significant difference in erodibility found for disturbed or sealed soils.
	🔴	Warren et al 1986	Short-duration grazing at progressively increased stocking rates progressively decreased infiltration and increased erosion compared to no grazing.
	🔴	Pluhar et al 1987	Infiltration rates were lowest and sediment production was highest under rotational grazing compared to moderate continuous grazing.

Productivity	🟢	Briske et al 2014	Greater plant production found in high precipitation areas with intensive rotational grazing
	🟢	Hensler et al 2007	An additional 1645lb/ac of hay was harvested from MIG fields. Cows on MIG had greater weight gain and were able to graze for longer.
	🟢	Sanjari et al 2008	Time controlled grazing had higher herbage production than continuous grazing
	🟢	Sollenberger et al 2007	85% of reviewed papers reported an advantage in forage quantity or carrying capacity for rotational grazing
	⚪	Biondini & Manske 1996	No significant differences in ANPP or animal production (mass gains) across treatments
	⚪	Hall et al 2014	No significant differences found between the three stocking methods for herbage mass
	⚪	Heitschmidt et al 1987a	No significant differences of ANPP between different stocking rates
	⚪	Heitschmidt et al 1987b	Total standing crop greater with continuous grazing than planned, but quality is lower
	⚪	Holechek et al 2000	Generally no difference in production if stocking rates are equal
	⚪	Manley et al 1997	Grazing strategy had no effect on above-ground biomass
	⚪	Martin & Severson 1988	Differences among pastures in herbage production are attributed mainly to climate and were not materially altered by grazing treatment
	🔴	Briske et al 2008	Meta-analysis found an advantage of rotational grazing in forage quantity (compared to continuous grazing) in just 13% of studies

A.9. Additional related literature not categorized above

Author	**Year**	**Location**	**Length of study (years)**	**Type of intensive rotational grazing studied**
Conant et al	2003	Virginia	Single sample, management practices at each site had been in place for 3-25 years	Management intensive grazing
Dormaar, Smoliak, Wilms	1989	Alberta, Canada	4	Short-duration grazing
Additional papers analysed in Briske et al 2008 meta-analysis				
Anderson	1988	New Mexico	2	SDG
Bagdan & Kidner	1967	Kenya	5	Rotational, deferred rotational
Barnes & Denny	1991	Zimbabwe	6	SDG
Cassels et al.	1995	Oklahoma	5	SDG
Derner & Hart	2007	Wyoming	25	SDG
Derner & Hart	2007b	Colorado	9	SDG
Fisher & Marian	1951	Texas	8	Rotational
Fourie & Engels	1986	South Africa	4	SDG
Fourie et al.	1985	South Africa	4	SDG
Gillen et al.	1998	Oklahoma	5	SDG
Gutman	1990	Israel	2	Rotational

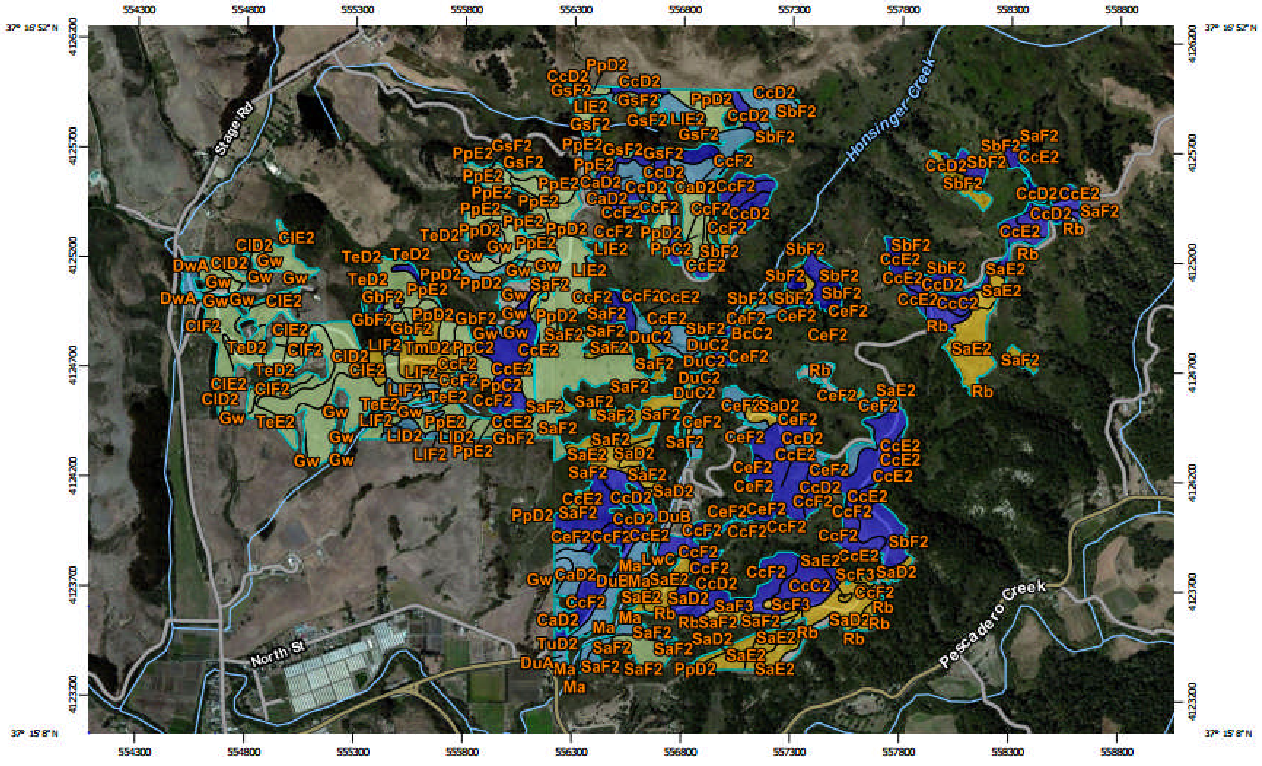
Gutman & Seligman	1979	Israel	10	Rotational
Hart et al.	1993	Wyoming	5	SDG
Hart et al.	1988	Wyoming	6	SDG and deferred rotation
Heady	1961	California	5	Deferred rotation
Hepworth et al..	1991	Wyoming	4	SDG and deferred rotation
Hirschfield et al.	1996	North Dakota	2	SDG
Holecheck et al.	1987	Oregon	5	Rest-rotation and deferred rotation
Hubbard	1951	Alberta, Canada	6	Deferred rotation
Hyder & Sawyer	1951	Oregon	11	Rotational
Jacobo et al.	2000	Argentina	3	SDG
Kirby et al.	1986	North Dakota	2	SDG
Kothman et al.	1971	Texas	8	Merrill
Kreuter et al.	1984	South Africa	3	SDG
Laycock and Conrad	1981	Utah	7	Rest-rotation
Martin & Ward	1976	Arizona	7	Alternative-year seasonal rest
McCollum et al.	1999	Oklahoma	5	SDG
McIlvain & Savage	1951	Oklahoma	9	Rotational
Merrill	1954	Texas	4	Merrill
Murray and Klemmedson	1968	Idaho	3	Seasonal rotation
Owensby et al.	1973	Kansas	17	Deferred rotation
Pitts & Bryant	1987	Texas	4	SDG
Ratliff	1986	California	8	Rotational
Reardon & Merrill	1976	Texas	20	Deferred rotation
Rogler	1951	North Dakota	25	Deferred rotation
Smaliak	1960	Alberta, Canada	9	Deferred rotation
Volesky et al.	1990	South Dakota	2	SDG
Walker & Scott	1968	Tanzania	2	Rotational
White et al.	1991	New Mexico	6	SDG
Winder & Beck	1990	New Mexico	17	3-pasture rotation
Wood & Blackburn	1984		5	High-intensity/low-frequency and deferred rotation
Additional papers analysed in Sollenberger et al 2007 meta-analysis				
Aiken	1998	Arkansas	2	3 and 11-paddock rotational grazing
Bertelsen et al	1993	Illinois	2	6 and 11-paddock rotational grazing
Bryant et al	1961	Virginia	2	10-paddock rotational grazing
Chapman et al	2003	Victoria, Australia	3	4-paddock rotational grazing

Davis and Pratt	1956	Ohio	3	6-paddock rotational grazing
Hoveland et al	1997	Georgia, USA	3	12-paddock rotational grazing
Hull et al	1967	California	3	6-paddock rotational grazing
Mathews et al	1994b	Florida	2	15-paddock rotational grazing
Popp et al	1997b	Connecticut	3	10-paddock rotational grazing
Stewart et al	2005	Florida	3	4 different rotational grazing treatments
Tharel	1989	Arkansas	Unknown	Rotational grazing
Volesky	1994	Oklahoma	1	frontal rotational grazing
Volesky et al	1994	Oklahoma	2	2-paddock rotational and frontal rotational grazing

A.10. Available water holding capacity

Figure 14: Map of available water holding capacity for TomKat Ranch grasslands (NRCS 2014)

Based on survey area data version 8 (Sep 17, 2014)



Soil Rating Points

🟥 <= 0.08

🟨 > 0.08 and <= 0.11

🟩 > 0.11 and <= 0.13

🟦 > 0.13 and <= 0.15

🟦 > 0.15 and <= 0.18

⬜ Not rated or not available

Table 31: Available water holding capacity for 0 to 80cm for TomKat Ranch grasslands

Weighted average: 9.9564 cm

Map unit symbol	Map unit name	Rating (cm)	Acres in AOI	Percent of AOI
BcC2	Botella clay loam, sloping, eroded	14.4	1.8	0.20%
CaD2	Cayucos clay, moderately steep, eroded	11.4	25.1	3.20%
CcC2	Cayucos clay loam, sloping, eroded	11.78	16.4	2.10%
CcD2	Cayucos clay loam, moderately steep, eroded	11.78	103.1	13.30%
CcE2	Cayucos clay loam, steep, eroded	11.78	97.4	12.50%
CcF2	Cayucos clay loam, very steep, eroded	11.78	23.3	3.00%
CeF2	Cayucos stony clay loam, very steep, eroded	10.26	16.4	2.10%
ClD2	Colma loam, moderately steep, eroded	12	34.4	4.40%
ClE2	Colma loam, steep, eroded	12	27	3.50%
ClF2	Colma loam, very steep, eroded	12.09	8.3	1.10%
CsB	Corralitos sandy loam, gently sloping	6.98	0.3	0.00%
DuA	Dublin clay, nearly level	12	2	0.30%
DuB	Dublin clay, gently sloping	12	12.7	1.60%
DuC2	Dublin clay, sloping, eroded	12	7	0.90%
DwA	Dublin clay, nearly level, imperfectly drained	12	2.8	0.40%
GbF2	Gazos loam, very steep, eroded	10.28	2.9	0.40%
GsF2	Gazos and Lobitos stony loams, very steep, eroded	7.19	7.8	1.00%

Gw	Gullied land (tierra and watsonville soil materials)		12	1.50%
LlD2	Lobitos loam, moderately steep, eroded	12	3	0.40%
LlE2	Lobitos loam, steep, eroded	12	17.1	2.20%
LlF2	Lobitos loam, very steep, eroded	12	7.7	1.00%
LwC	Lockwood loam, sloping, seeped	12.56	5.9	0.80%
Ma	Mixed alluvial land	8.27	2	0.30%
PpC2	Pomponio loam, sloping, eroded	9.56	18.3	2.40%
PpD2	Pomponio loam, moderately steep, eroded	9.56	96	12.40%
PpE2	Pomponio loam, steep, eroded	9.56	49.6	6.40%
Rb	Rough broken land		7.2	0.90%
SaD2	Santa Lucia loam, moderately steep, eroded	6.82	36.9	4.70%
SaE2	Santa Lucia loam, steep, eroded	6.82	32.5	4.20%
SaF2	Santa Lucia loam, very steep, eroded	6.82	24.4	3.10%
SaF3	Santa Lucia loam, steep and very steep, severely eroded	5.6	4.6	0.60%
SbF2	Santa Lucia stony loam, very steep, eroded	6.82	12.1	1.60%
ScF3	Santa Lucia stony loam, very shallow, steep and very steep, severely eroded	2.7	3.5	0.50%
TeD2	Tierra loam, moderately steep, eroded	8.3	4.8	0.60%
TeE2	Tierra loam, steep, eroded	8.3	29.1	3.70%
TmD2	Tierra sandy loam, moderately steep, eroded	6.58	16.3	2.10%
TuD2	Tunitas clay loam, moderately steep, eroded	12.6	4.5	0.60%

A.11. Soil evaporation coefficient

The soil evaporation coefficient required by IFSM is the stage 1 (atmosphere limited) evapotranspiration coefficient (E_{so}). This can be calculated using the following formulae (Allen et al. 1998 Annex 7):

$E_{so} = 1.15\ ET_o$, where

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

where:
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],
 slope vapour pressure curve [kPa °C-1],
 psychrometric constant [kPa °C-1].

E_{so} is dependent on various atmospheric/meteorological factors. However, we do not have these data for TomKat.

This equation is from the FAO's crop evapotranspiration guidelines. E_{so} represents the potential (first stage) evapotranspiration from bare soil. The value 1.15 represents increased evaporation potential due to low albedo of wet soil and the possibility of heat stored in the surface layer during previous dry periods.

A.12. Runoff curve

The SCS Runoff Curve Number method is developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) and is a method of estimating rainfall excess from rainfall (Hjelmfelt, 1991).

The runoff curve number is determined by: (1) land use; (2) hydrological condition; and (3) hydrological soil group.

For TomKat, the land use of interest is pasture, the hydrological condition is 'Fair', and the predominant soil group is Group C (see A.3.1 and A.3.2). According to Cronshey et al (1986), the appropriate runoff curve number is therefore 79 (Table 32).

Table 32: Runoff curve numbers for pasture, grassland, or range (Cronshey et al. 1986, Table 2.2a)

Cover description		**Curve numbers for hydrologic soil group**			
Cover type	**Hydrologic condition**	**A**	**B**	**C**	**D**
Pasture, grassland, or range—continuous forage for grazing.	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80

A.12.1. Land use and hydrological condition

According to Cronshey et al. (1986), there are three hydrological condition categories for pasture/grassland/range. These are defined as follows:

- Poor: <50% ground cover or heavily grazed with no mulch
- Fair: 50-75% ground cover and not heavily grazed
- Good: : >75% ground cover and light or only occasionally grazed.

In 2014, there were significant amounts of bare ground and dry thatch at TomKat, which meant that ground cover was approximately 77%. Therefore, we consider it prudent to categorize TomKat's hydrological condition as overall 'Fair' quality.

A.12.2. Hydrological soil group

There are four categories of hydrological soil group (Cronshey et al. 1986, Appendix A):

- Group A: Lowest runoff potential. High infiltration rate even when soil is thoroughly wetted. Consist of deep, well to excessively drained sand or gravel with high rate of water transmission (more than 8mm/hr).
- Group B: Moderate runoff potential. Chiefly of moderately deep, moderately well drained soils with moderately fine or moderately coarse textures.
- Group C: Moderately high runoff potential. Low infiltration rates when thoroughly wetted. Soils of moderately fine to fine texture.
- Group D. High runoff potential. Very low infiltration rates when thoroughly wetted and consist of clay soils with high swelling potential, soils with high water table, and shallow soils over nearly impervious material.

According to NRCS Soil Survey (2014), TomKat consists of predominantly category C soils (Figure 15 and Table 32).

Figure 15: Map showing hydrological soil groups for TomKat Ranch grasslands (NRCS 2014)

Based on survey area data version 8 (Sep 17, 2014)

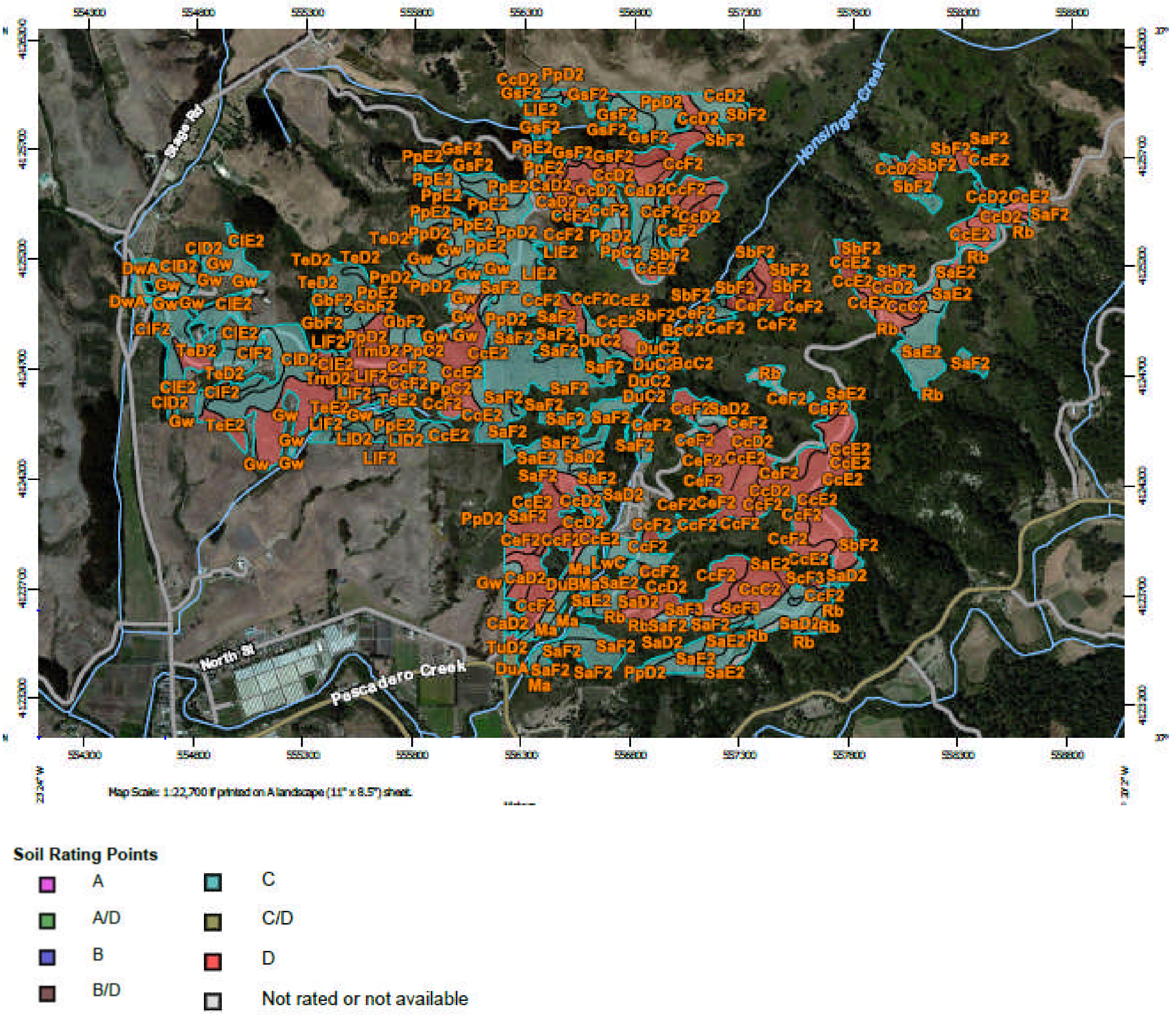


Table 33: Hydrological soil groups for TomKat Ranch grasslands

Dominant hydrological soil group is C (53.5% of total). Second highest soil group is D (43.1%).

Map unit symbol	Map unit name	Hydrological soil group	Acres in AOI	Percent of AOI
BcC2	Botella clay loam, sloping, eroded	C	1.8	0.20%
CaD2	Cayucos clay, moderately steep, eroded	D	25.1	3.20%
CcC2	Cayucos clay loam, sloping, eroded	D	16.4	2.10%

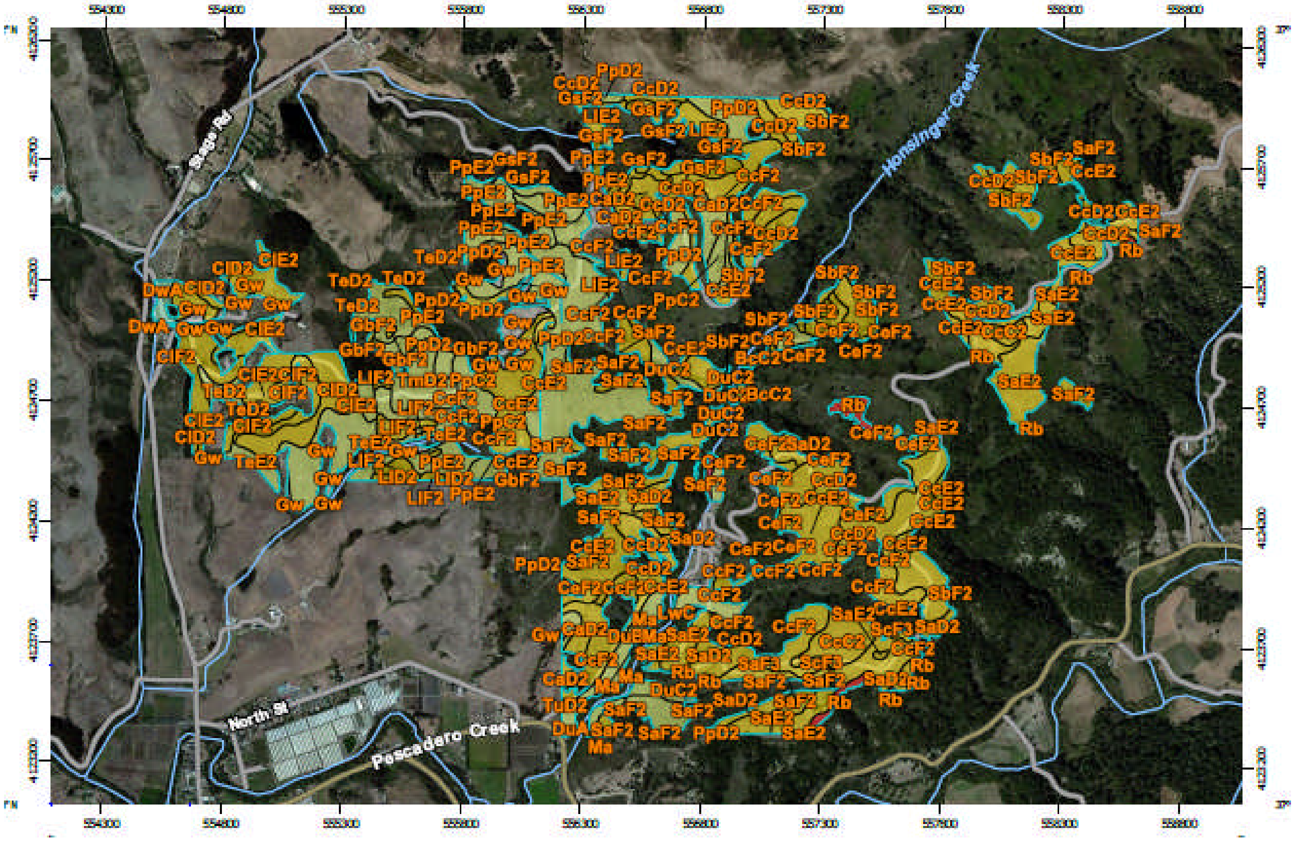
CcD2	Cayucos clay loam, moderately steep, eroded	D	103.1	13.30%
CcE2	Cayucos clay loam, steep, eroded	D	97.4	12.50%
CcF2	Cayucos clay loam, very steep, eroded	D	23.3	3.00%
CeF2	Cayucos stony clay loam, very steep, eroded	D	16.4	2.10%
ClD2	Colma loam, moderately steep, eroded	C	34.4	4.40%
ClE2	Colma loam, steep, eroded	C	27	3.50%
ClF2	Colma loam, very steep, eroded	C	8.3	1.10%
CsB	Corralitos sandy loam, gently sloping	A	0.3	0.00%
DuA	Dublin clay, nearly level	C/D	2	0.30%
DuB	Dublin clay, gently sloping	C	12.7	1.60%
DuC2	Dublin clay, sloping, eroded	C	7	0.90%
DwA	Dublin clay, nearly level, imperfectly drained	C/D	2.8	0.40%
GbF2	Gazos loam, very steep, eroded	C	2.9	0.40%
GsF2	Gazos and Lobitos stony loams, very steep, eroded	C	7.8	1.00%
Gw	Gullied land (tierra and watsonville soil materials)		12	1.50%
LlD2	Lobitos loam, moderately steep, eroded	C	3	0.40%
LlE2	Lobitos loam, steep, eroded	C	17.1	2.20%
LlF2	Lobitos loam, very steep, eroded	C	7.7	1.00%
LwC	Lockwood loam, sloping, seeped	C	5.9	0.80%
Ma	Mixed alluvial land		2	0.30%
PpC2	Pomponio loam, sloping, eroded	C	18.3	2.40%
PpD2	Pomponio loam, moderately steep, eroded	C	96	12.40%
PpE2	Pomponio loam, steep, eroded	C	49.6	6.40%
Rb	Rough broken land		7.2	0.90%
SaD2	Santa Lucia loam, moderately steep, eroded	C	36.9	4.70%

SaE2	Santa Lucia loam, steep, eroded	C	32.5	4.20%
SaF2	Santa Lucia loam, very steep, eroded	C	24.4	3.10%
SaF3	Santa Lucia loam, steep and very steep, severely eroded	C	4.6	0.60%
SbF2	Santa Lucia stony loam, very steep, eroded	C	12.1	1.60%
ScF3	Santa Lucia stony loam, very shallow, steep and very steep, severely eroded	D	3.5	0.50%
TeD2	Tierra loam, moderately steep, eroded	D	4.8	0.60%
TeE2	Tierra loam, steep, eroded	D	29.1	3.70%
TmD2	Tierra sandy loam, moderately steep, eroded	D	16.3	2.10%
TuD2	Tunitas clay loam, moderately steep, eroded	C	4.5	0.60%

A.13. Whole profile drainage coefficient

Figure 16: Map of drainage class for TomKat Ranch grasslands (NRCS Soil Survey 2014)

Based on survey area data version 8 (Sep 17, 2014)



🟥 Excessively drained

🟧 Somewhat excessively drained

🟨 Well drained

🟩 Moderately well drained

🟩 Somewhat poorly drained

🟦 Poorly drained

🟪 Very poorly drained

🟦 Subaqueous

⬜ Not rated or not available

Table 34: Drainage class by soil type for TomKat Ranch grasslands (NRCS Soil Survey 2014)

65.1% of our soils are considered 'well-drained', and 31.8% are considered 'moderately well-drained'.

Map unit symbol	Map unit name	Drainage class	Acres in AOI	Percent of AOI
BcC2	Botella clay loam, sloping, eroded	Well drained	1.8	0.20%
CaD2	Cayucos clay, moderately steep, eroded	Well drained	25.1	3.20%
CcC2	Cayucos clay loam, sloping, eroded	Well drained	16.4	2.10%
CcD2	Cayucos clay loam, moderately steep, eroded	Well drained	103.1	13.30%
CcE2	Cayucos clay loam, steep, eroded	Well drained	97.4	12.50%
CcF2	Cayucos clay loam, very steep, eroded	Well drained	23.3	3.00%
CeF2	Cayucos stony clay loam, very steep, eroded	Well drained	16.4	2.10%
ClD2	Colma loam, moderately steep, eroded	Well drained	34.4	4.40%
ClE2	Colma loam, steep, eroded	Well drained	27	3.50%
ClF2	Colma loam, very steep, eroded	Well drained	8.3	1.10%
CsB	Corralitos sandy loam, gently sloping	Somewhat excessively drained	0.3	0.00%
DuA	Dublin clay, nearly level	Moderately well drained	2	0.30%
DuB	Dublin clay, gently sloping	Moderately well drained	12.7	1.60%
DuC2	Dublin clay, sloping, eroded	Moderately well drained	7	0.90%
DwA	Dublin clay, nearly level, imperfectly drained	Somewhat poorly drained	2.8	0.40%
GbF2	Gazos loam, very steep, eroded	Well drained	2.9	0.40%
GsF2	Gazos and Lobitos stony loams, very steep, eroded	Well drained	7.8	1.00%
Gw	Gullied land (tierra and watsonville soil materials)		12	1.50%
LlD2	Lobitos loam, moderately steep, eroded	Well drained	3	0.40%
LlE2	Lobitos loam, steep, eroded	Well drained	17.1	2.20%
LlF2	Lobitos loam, very steep, eroded	Well drained	7.7	1.00%
LwC	Lockwood loam, sloping, seeped	Moderately well drained	5.9	0.80%
Ma	Mixed alluvial land	Excessively drained	2	0.30%
PpC2	Pomponio loam, sloping, eroded	Moderately well drained	18.3	2.40%

PpD2	Pomponio loam, moderately steep, eroded	Moderately well drained	96	12.40%
PpE2	Pomponio loam, steep, eroded	Moderately well drained	49.6	6.40%
Rb	Rough broken land	Excessively drained	7.2	0.90%
SaD2	Santa Lucia loam, moderately steep, eroded	Well drained	36.9	4.70%
SaE2	Santa Lucia loam, steep, eroded	Well drained	32.5	4.20%
SaF2	Santa Lucia loam, very steep, eroded	Well drained	24.4	3.10%
SaF3	Santa Lucia loam, steep and very steep, severely eroded	Well drained	4.6	0.60%
SbF2	Santa Lucia stony loam, very steep, eroded	Well drained	12.1	1.60%
ScF3	Santa Lucia stony loam, very shallow, steep and very steep, severely eroded	Well drained	3.5	0.50%
TeD2	Tierra loam, moderately steep, eroded	Moderately well drained	4.8	0.60%
TeE2	Tierra loam, steep, eroded	Moderately well drained	29.1	3.70%
TmD2	Tierra sandy loam, moderately steep, eroded	Moderately well drained	16.3	2.10%
TuD2	Tunitas clay loam, moderately steep, eroded	Moderately well drained	4.5	0.60%