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A novel model to estimate the impact of Coal Seam Gas extraction on agro-economic returns

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ABSTRACT

There is an ever growing demand for energy worldwide and the demand for gas alone is predicted to double between 2010 and 2035. This demand together with concurrent advances in drilling technologies caused the production of unconventional natural gas such as shale gas and coal seam gas (CSG), which is in the focus of this paper, to grow rapidly in the last decades. With the gas bearing coal seams extending across vast areas within their respective basins and with CSG production having to follow these seams through a network of production wells, pipelines and access roads, CSG activity affects large areas and therefore interferes with existing land uses, predominantly agriculture. For the eastern Australian Surat Basin and the southern Bowen Basin alone there are projected well numbers in excess of 15,000 to 20,000 between the years 2020 and 2030. The interference of CSG with agriculture on a large scale has raised concerns about the impact of CSG on farmland, food security, water resources and the socio-economic environment within the affected regions and beyond. This paper presents a newly developed spatial model which provides order of magnitude figures of the impact of CSG activity on gross economic returns of current agricultural land uses in a given region over the time of CSG production. The estimated gross figures do not account for any compensation payments received by farmers. The model is capable of accounting for a variation in a variety of parameters including impact frequency of distinct infrastructure elements, differences in soil types and associated varying responses of soil productivity, varying length of the CSG production phase and more. The model is flexible in that it can be transferred and applied in other regions as well. Based upon a literature review and given that CSG is an industry that started operating at larger scales relatively recently, we claim that the presented model is the first of its kind to provide these important agro-economic indicators.

1. Introduction

The demand for energy is growing worldwide and the demand for gas alone is predicted to double between 2010 and 2035 (Lyster, 2012). This ever growing demand as well as advances in drilling technologies caused the production of unconventional natural gas such as shale gas and coal seam gas (CSG) to grow rapidly in the last decades. CSG resources in eastern Australia are to complement the conventional, largely offshore, gas resources (Jaques et al., 2010) and annual CSG production in Australia increased from 1 PJ in 1996 to 240 PJ in 2010–11 (Geoscience Australia, 2012). With estimated Economic Demonstrated Resources (EDR) of around 35,900 PJ and taking the 2010–11 production rates as a baseline CSG reserves can be projected to last some 150 years. This does not account for Australia's substantial sub-economic demonstrated resources of 65,500 PJ and "very large" inferred CSG resources (Geoscience Australia, 2012).

Of the 35,900 PJ in EDR, some 92% (or 33,000 PJ) are in Queensland and the remaining 2900 PJ in New South Wales. Nearly all current reserves are contained in the Surat (69%) and Bowen (23%) basins with smaller amounts distributed across basins in New South Wales (Clarence-Moreton (1%), Gunnedah (4%), Gloucester and Sydney basin (Geoscience Australia, 2012; Moore, 2012). While CSG production was largely centred in the Bowen Basin in the mid 1980s to 1990s, the Walloon subgroup, a geological coal seam bearing unit in the Surat Basin, became the focus of gas companies from the year 2000 (Queensland Government, 2008). Fig. 1 shows the major coal basins of Australia.

Another factor that contributed to the rapid increase in the production of this energy source is the growing awareness of the implications of the release of greenhouse gas (GHG) emissions on climate which forces governments to consider the implementa-

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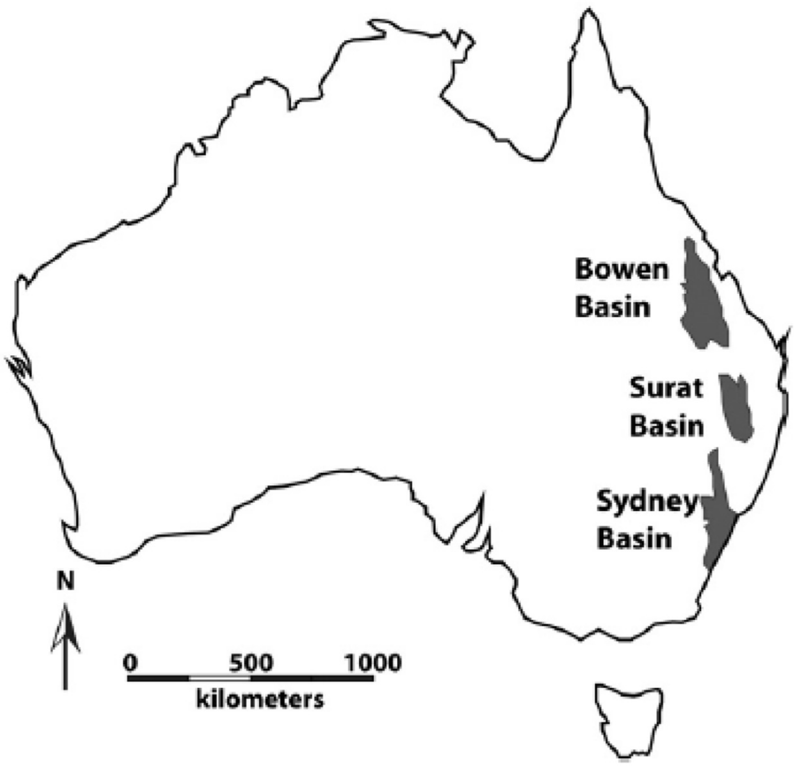


Fig. 1. Coal basins in Australia (from Moore, 2012).

tion of cleaner forms of energy (Poisel, 2012) and the production of electricity through the combustion of natural gas produces less GHG emissions than that from coal (Kember, 2012). However when comparing the life cycle GHG intensities per MWh of electricity produced Hardisty et al. (2012) found that the technology used in the combustion of gas can affect the degree of GHG intensity. Some authors (Kember, 2012; Hardisty et al., 2012) also point towards the necessity to include fugitive emissions from gas operations in these life cycle calculations e.g. at well sites or along pipelines. Hardisty et al. (2012) considered these emissions to be manageable by applying best practice. A recent study (Day et al., 2014) showed that fugitive emissions of the Australian CSG industry are below 1–2% and were considered very low compared to overall production.

Gas bearing coal seams extend across vast areas within their respective basins. CSG production follows these seams through a network of production wells, pipelines and access roads. CSG activity therefore affects large areas and interferes with existing land uses – predominantly agriculture. Klohn Crippen Berger Ltd (2012) provide estimates of active wells in excess of 15,000 to 20,000 between the years 2020 and 2030 for the Surat basin and the southern Bowen basin in Queensland. Given an average well density of one to two wells per square kilometre and accounting for all the infrastructure associated to wells the total area footprint will be substantial.

The interference of CSG with agriculture on a large scale has raised concerns about the impact of CSG on farmland and food security in Australia (Lyster, 2012) and in the U.S. where the impacts of shale gas production in the Pennsylvanian Marcellus shale on forest ecosystems and surface water were discussed by various authors (Drohan et al., 2012; Rahm and Riha, 2012; Olmstead et al., 2013; Drohan and Brittingham, 2012). Australian state governments are aware of these issues and are committed to strategies which involve a simultaneous increase of primary production and resource production while reducing GHG (Owens, 2012).

In Australia cropping land resources and related industries are considered key components of the economy. In Queensland alone the gross value of agricultural production was estimated at $13.7 billion in 2012-13 with an estimated 324,000 people employed across the whole food supply chain (Qld DAFF, 2013). In order to protect and preserve land that is highly suitable for cropping and to facilitate strategic planning the Queensland Government has imposed a variety of legislative frameworks (Queensland Government, 1992; Queensland DPI and DHLGP, 1993). More recent legislation includes the Strategic Cropping Land Act. This Act was repealed in June 2014 by the Regional Planning Interests Act 2014 (RPI Act) (Queensland Government, 2014) which provides a single integrated legislative framework that applies various existing policies including existing strategic cropping land policies. This legislation is intended to protect and preserve of the most valuable agricultural land and manage impacts of development on that land.

Agriculture has been the mainstay of economic development in southern Queensland, and the coal basins located there, throughout the 20th century (Schandl and Darbas, 2008). As such, agriculture has historically shaped regional landscapes and identities which, due to CSG development led by resource development, now face significant change. These changes and associated impacts are multifacetted and interfere with the biophysical, social and economic landscape.

The impacts that are subject of this paper are the impacts of CSG activity and its associated infrastructure elements on agricultural production and its returns. Because of the large scale of CSG development and its spatial intersection with agriculture there will be impacts on agricultural revenues due to:

- direct impacts on the soil resource base in that fertile soils will be compacted or removed and stockpiled (and later used for rehabilitation) resulting in reduced soil productivity, and
- the spatial footprint associated to CSG infrastructure elements which is equal to taking land out of production.

Due to the diversity of soils and the diversity of impact signatures (both areal and temporal) of CSG infrastructure elements the magnitude of the impact on agricultural revenues and losses to production in space and time is hard to estimate. Meanwhile the relative recent rise of CSG production has revealed a gap in methods to quantify the impact in terms of revenues lost ($) and production lost (t) across various spatial scales. The provision of estimates of these important agro-economic indicators is important information for farmers, communities as well as governmental bodies and resource companies alike as it represents another important piece of information in the multi-facetted picture of impacts and benefits related to CSG production.

This paper presents a new process that accounts for the diversity of impact characteristics related to CSG infrastructure. This process consistently integrates land use and economic information to provide estimates of the impact of CSG on agro-economic returns. It also describes the approach to operationalise the estimation process which is flexible in that a variety of uncertain boundary conditions can be changed. The process can also be applied in other regions where broad scale land use planning and economic impact assessment in the context of CSG production is required.

2. Study area

The Surat basin is a geological basin which covers considerable areas of northern New South Wales and southern Queensland. The coal formation occurred within the basin during the Jurassic period, about 200-145 million years ago (Vink et al., 2008). CSG is produced from multiple coal seams across the Middle Jurassic Walloon Subgroup (Hamilton et al., 2012) and petroleum leases have already been approved for tenements covering over 24,000 km^2 of the Surat basin. These tenements are held by a variety of resource companies. The study area is located in the central Condabri gas development area which is one of many tenements where Australia Pacific Liquefied Natural Gas (APLNG) holds the permit to extract gas (Fig. 2).

The Condabri development area has a total area of nearly 46,000 ha. The land use is almost exclusively agricultural. About 85% of the land use is dedicated to livestock grazing; 9% is cropping which includes about 1% of irrigated cropping. About 3% is dedicated to production forestry. The study area extends across approximately 11,500 ha of which 79% is dedicated to grazing, about 18% to cropping and 2% to irrigated cropping. All agricultural land in the study area is freehold land which is land owned absolutely by an owner. A freehold owner has the right to sell or lease the land and collect rent (Queensland Government, 2015). The land that provides the space for major CSG infrastructure for example the water- and gas treatment plants as well as dams and ponds are owned by the CSG operator.

3. CSG infrastructure

The way CSG is extracted and the associated supply chain is described in greater detail by Moore (2012) or Geoscience Australia (2012). While no attempt is made here to reproduce this discussion this section aims at providing CSG infrastructure terminology which will be used throughout the remainder of this paper.

To access the gas bearing coal seams a well has to be drilled into the ground. When a well is drilled heavy machine equipment, borehole casings etc. need to be around the well site. To minimise the spatial impact these operations are constrained to standardised areas called "lease areas", which in the study area, are about 1 ha in size. During gas production it may be necessary to repeatedly access lease areas for well workovers. The area right next to and around the well is a compacted area called "hardstand" area. This hardstand area extends a few 100 m^2 in size and provides space for the gas water separation unit. Once separated, gas and water flow along underground pipelines ("flowlines") to nearby processing facilities, gas and water treatment facilities, respectively. At the gas processing plant the gas is further cleaned, compressed and subsequently transported along pipelines ("main pipeline") to either Australian customers or to a facility that turns the gas into liquefied natural gas (LNG) for overseas export. The CSG water requires treatment and is directed towards a water treatment facility which also provides dams and storage ponds as buffer storage before entering the treatment facility. To access the wells a network of access tracks has to be established. Furthermore there are vents along the pipelines and stockpile areas for the deposition of all sorts of materials. Fig. 3 shows the CSG infrastructure network within the study area including gas and water treatment facilities and water storage ponds in the south western corner. The total footprint of all infrastructure elements in the study area amounts to around 920 (ha).

Fig. 4 shows the areas associated to individual infrastructure elements in the study area and the land use across which these infrastructure elements extend.

4. Methods and data

4.1. Data layers

The digital data layers include information about land use, soil types, good quality agricultural land (GQAL), strategic cropping land (SCL), cadastral information, information about CSG infrastructure as well as economic layers which capture the average returns in ($/ha) and (t/ha) for a specific agricultural land use in the study area. While virtually all biophysical and administrative information was sourced from Queensland government websites the CSG infrastructure data were obtained from the CSG producer (APLNG).

Table 1 gives an overview of the data that were used and provides information as to where data were sourced from.

4.2. Economic data

Economic data were sourced from the Australian Bureau of Statistics (ABS) that conducts an agricultural census on a regular basis. Due to a variety of factors, for example climate or world market prices, yields and agricultural revenues may substantially vary from year to year. To accommodate these fluctuations, average revenues from the last 20 years of census data were applied. All ($) values used in this analysis were expressed in ($) values of the year 2011 though which was the most recent census year at the time of writing this paper. All economic data were spatially associated to 1 km^2 pixels using a profit map system developed by Marinoni et al. (2012).

4.3. Spatial footprint of infrastructure elements

The developed method allows for the inference of the impact of CSG activity on agricultural production and economic returns. The impact assessment is based on the fact that the establishment of CSG infrastructure, a new access track for instance, removes land from agricultural production. This means that economic returns in ($/ha) are reduced and production in tonnes (t) is lost for as long as the infrastructure element exists. With the infrastructure data being digitally available the spatial footprint in (ha) of the infrastructure elements can be easily determined using standard GIS functionality. While the size of the footprint is an important factor that substantially drives the magnitude of the impact there are various other factors that need to be considered such as

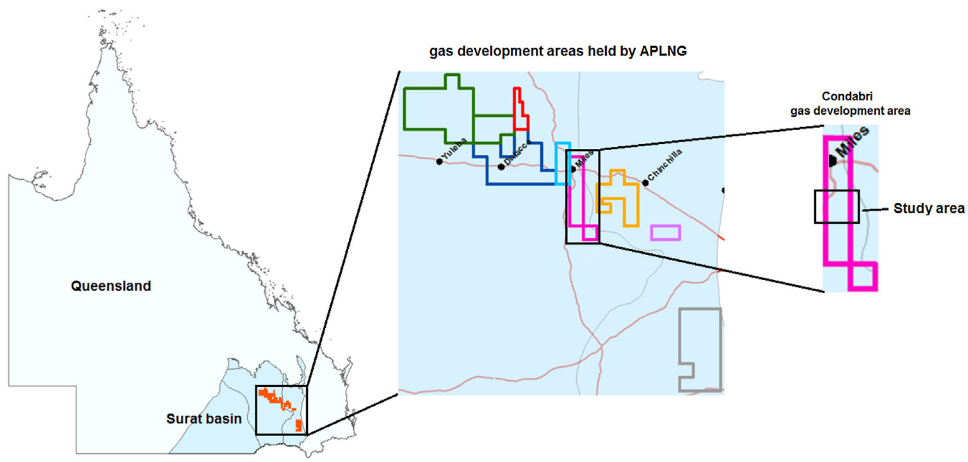


Fig. 2. APLNG tenements in the Queensland part of the Surat basin. Study area is in the central part of the Condabri gas development area.

Fig. 3. Left: CSG infrastructure network in the study area consisting of well pads, access tracks, gas treatment and water treatment facilities in the study area. E-W width of the development area ca. 8.3 km, N-S extent of the study area approx. 12 km. Right: Example of an access track and a well pad in the field.

1. Change of land use. CSG infrastructure intersects with a variety of agricultural land uses where each land use has a specific return ($/ha, tonnes of a commodity produced).
2. Diversity of CSG infrastructure elements. There is not only one but a variety of CSG infrastructure elements that need to be considered (access tracks, well pads, pipelines etc.).
3. Diversity of impact "signature". CSG infrastructure elements have distinct impact signatures not only in terms of the spatial footprint but also in term of impact time, magnitude and frequency.
4. Changes in the biophysical environment. Infrastructure elements as well as land uses spatially intersect with a variety of soil types where each soil type is not only different in terms of productivity and economic returns but also in terms of its reaction to impacts.

The authors are aware that there is a range of additional factors related to CSG production which impact agricultural activity and productivity such as the interruption of farming operations, dust generation, erosion etc. A discussion of these factors which are not covered by the presented method is provided in Section 4.9 of this paper.

The following sections describe the impact assessment method in greater detail including data requirements as well as the concept along soil recovery and impact typology.

4.4. Soil impacts and soil recovery

During construction of CSG infrastructure heavy machine equipment is used which severely disturbs the existing soil texture through compaction which is equivalent to decreasing soil porosity and increasing soil strength. This impacts productivity in that it limits access to water and nutrients and makes it harder for seedlings to grow. Impacts of compaction on soils are well studied and soil compaction is generally considered a problem if not a threat to agriculture (Hakansson, 1994; Duiker, 2004; Hamza and Anderson, 2005). It is known though that soils have a capacity to reverse compaction (through wetting-drying, freeze-thaw cycles – the latter are not relevant to the study area) but this process is slow. Duiker (2004) determined a 3% yearly decrease in yield

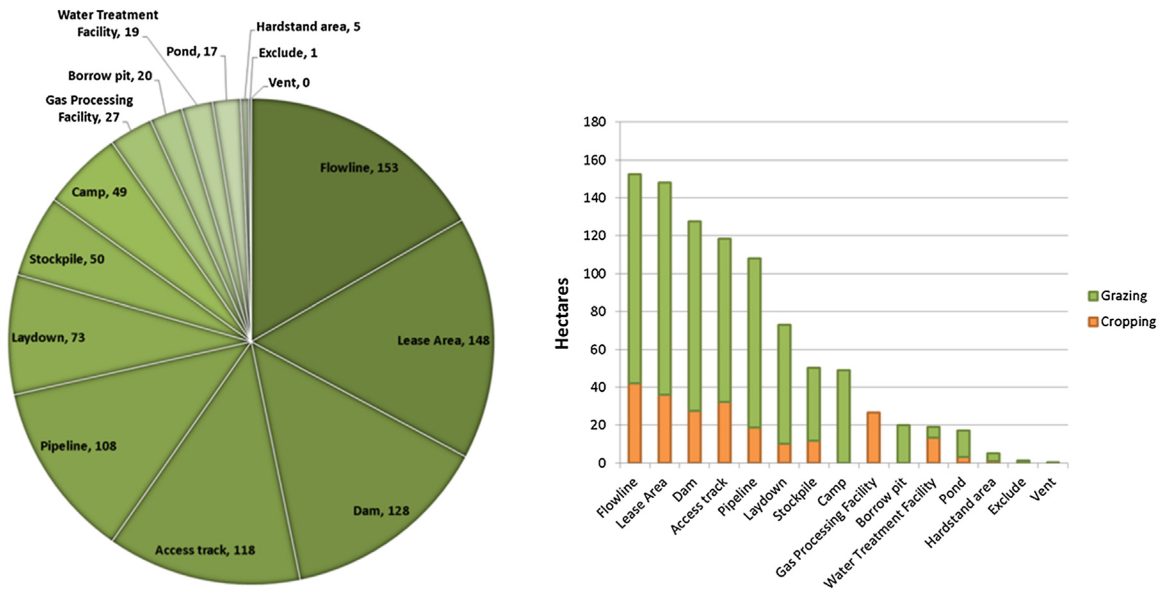


Fig. 4. Left: Area (ha) associated to individual types of infrastructure in the study area. Right: Area of land use across which infrastructure elements extend.

losses on soil compacted by a 10 ton axle load. Antille et al. (2014) reported a 50% decrease in productivity in CSG areas impacted by compaction with rehabilitated soils achieving values around 90% of the original productivity. In Queensland, mining operators are required by law to rehabilitate all areas of disturbance caused by their operations (Queensland Government, 1994). To model the gradual recovery, that is the increase of productivity in time, various linear and non-linear analytical options are available and can be applied to individual soils. The results presented in this paper are assuming a linear model of soil recovery.

4.5. Impact categories

There is no uniform temporal impact pattern which could be applied across all CSG infrastructure elements and even elements that serve the same purpose can have different temporal impact characteristics. For example while the development of a gas field would require new access tracks to be built, CSG companies would also endeavour to minimise the spatial footprint by using existing tracks and roads in the development area. While newly built access tracks add to the spatial footprint by removing additional area from agricultural production the use of existing tracks is a footprint that cannot be attributed to CSG. To account for the different impact characteristics a list of impact categories was developed which are provided in Table 2. In the access track example above, pre-existing access tracks would have to be assigned to a different impact category than the ones that are established for and rehabilitated after CSG.

Fig. 5 provides a schematic example of an impact signature of an impact category 2 used to estimate losses to agricultural production. The example provided shows an impact profile of an access track established at the beginning of CSG activity and rehabilitated after CSG production (assumed lifetime of CSG of 20 years). A value of 100% on the chart on the left hand side of Fig. 5 means that a piece of land is fully impacted in that it cannot contribute to production (note that the associated productivity profile on the right has values of 0% for the same period). After CSG production has finished the soil is rehabilitated and accessible to agriculture so that the impact consequently drops to zero. Due to the rehabilitation measures productivity bounces back (in this illustrative example to a value of 75% of the soil's original productivity) and gradually recovers in time (assuming a linear recovery) to its original productivity or very close to it. In this schematic example the original productivity is achieved after some 15 years after CSG production finished. This means that productivity impacts, even though diminishing in time, may go well beyond the lifetime of CSG production itself.

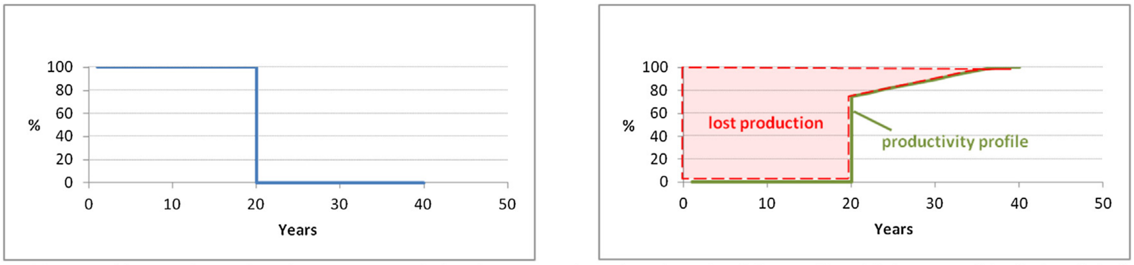
Losses attributed to the impact are represented in the area above the productivity profile (dashed outline, Fig. 5 right). These losses are quantitatively inferred using the area of the impacted area (ha), information about the land use before CSG and available data on the average production (t/ha) and average returns ($/ha) associated to this land use or the commodity produced, respectively. Further examples of impact categories are provided in Fig. 6.

Variations of impact profiles are possible in that for example the impact frequency for a certain infrastructure element can change. Fig. 6 (bottom) provides an example of one repeated impact after 12 years (12 years was picked for an illustrative purpose). It is possible though to assign more than one repeated impact and to vary the years after which an impact occurs.

It is highlighted here that the model provides a prognostic assessment. As such it is unknown for example how many work overs individual CSG wells will be undergoing during the time of CSG production. This lack of knowledge can however be met by integrating data based upon CSG production experience or field observations. If for example it was known that on average 10% of CSG wells will be undergoing 2 work overs, the model can randomly pick 10% of wells, associate the corresponding impact profile and compute the economic impact accordingly. Table 3 shows the impact categories assigned to distinct infrastructure elements. Note that according to the specifications provided in Table 3 "lease areas" are the only element subject to repeated impacts. Hardstand areas that are within lease areas would be repeatedly impacted as well. However hardstand areas are inaccessible to agriculture over the lifetime of the well therefore a category 2 was assigned.

4.6. Correction of the area footprint

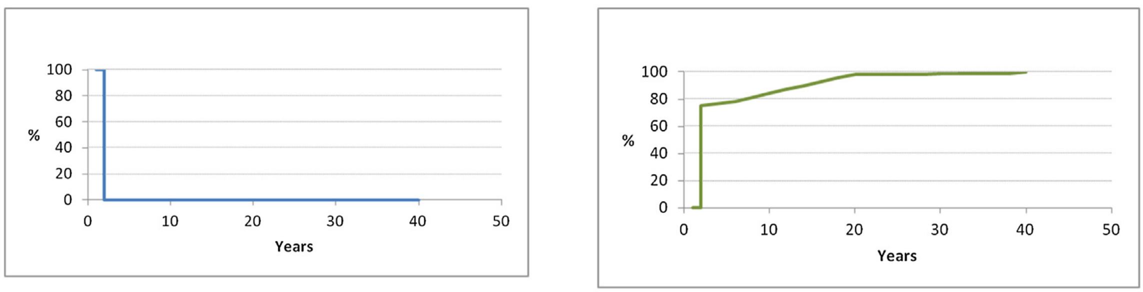
The nominal spatial footprint of CSG infrastructure elements in (ha or m^2) can be easily retrieved from the GIS layers. However, some infrastructure elements (e.g. pipeline vents) can act as obstacles to the farm operation in that they would require machine



Temporal impact footprint of an access track that is rehabilitated after 20 years

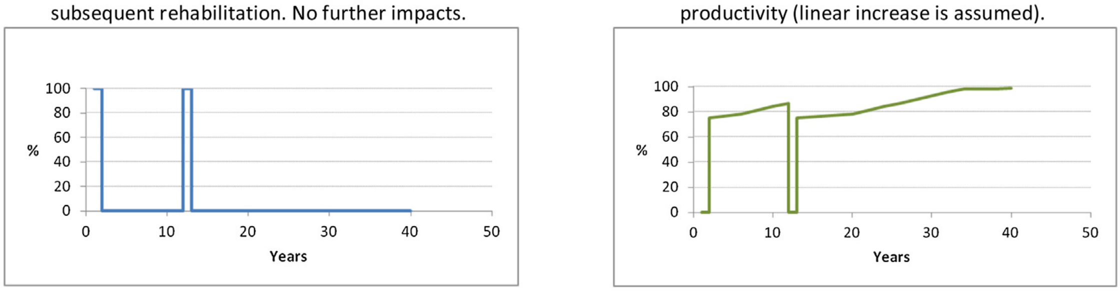
Associated productivity profile with loss area (shaded and dashed outline)

Fig. 5. Example impact profile for impact category 2 and associated productivity profile which captures the losses to agricultural production. See text for explanations.



Temporal impact footprint of a category 3 area, e.g. where a pipeline was established. Initial construction activity with subsequent rehabilitation. No further impacts.

Associated productivity profile. Productivity bounces back after rehabilitation followed by subsequent gradual increase in soil productivity (linear increase is assumed).



Temporal impact footprint of a category 4 area. E.g. the area around a production well (=lease area). Initial impact during setup. Repeated impact for a well work over after 12 years.

Same principle as above but repeated impact.

Fig. 6. Schematic example impact profiles for impact categories 3 (top) and 4 (bottom). For categories see Table 2.

GIS footprint of pipeline vent next to an access road

Footprint of pipeline vent next to an access road (field)

Corresponding “should be” footprint in the GIS

Fig. 7. Nominal footprint as shown in GIS (left). Observed footprint in the field (middle) and “should be” footprint in the GIS (right).

equipment to navigate around them. The real spatial footprint of some infrastructure elements can therefore be much larger than the nominal footprint (Fig. 7).

Farmers however do not deal with these obstacles in a uniform manner. While some farmers avoid infrastructure elements by leaving a buffer zone other farmers try to minimise this buffer so that the real area impact is just slightly larger than the nominal area impact. Depending upon the scale of the analysis and the number of nominal footprints to be rectified the analysis of high resolution aerial imagery or detailed field observations can be a solution to infer more appropriate real footprints for individual infrastructure elements. Another solution that is currently employed is the use of an average factor based upon a set of field observations the nominal area is to be multiplied with. This factor helps providing an estimate of an impact footprint that is larger than the nominal one. It is acknowledged that this introduces some inaccuracy. However, it is assumed that the total area that requires rectification is marginal compared to the total spatial footprint of all infrastructure

Table 1
Data used in the study including their sources. All data are vector data except for the economic layer which is in raster format.

Data layer	Source	Remark(s)
CSG development areas (tenements)	Qld Government	
Strategic cropping land (SCL)		
Good quality agricultural land (GQAL)		
Soil types		
Cadastral information		Location of lots
Land use		Vector map of 2009 (reworked 2012, download 2014)
Data on economic returns and productivity for specific land uses and commodities in the area	own data (CSIRO)	Average of time series of economic layers that were produced using the system described in Marinoni et al. (2012). Data in raster format. Link to vector land use data through a land use code which is common to both datasets.
CSG infrastructure including	CSG producer (APLNG)	
• Well locations (hardstand area)		Small fenced off area with well and gas/water separator (~ a few 100 m^2)
• Lease areas		Standardised area (~ 1 ha) around well location. Area is needed to establish a well and to provide space for drill rig, topsoil stockpile area etc. Lease areas need to be accessed for well workovers.
• Pipeline network (flowlines)		Pipelines to direct water and gas from the wells to processing facilities
• Access roads		Network of roads and tracks to access wells
• Vents along pipelines		
• Stockpile areas, Laydown areas		Areas for (temporary) storage of material
• Dams and water ponds		Buffer storage for water before entering the water treatment facility
• Gas treatment facility (GTF)		
• Water treatment facility (WTF)		
• Main pipeline		Pipeline corridor with main pipeline which transports gas to coastal ports for export

elements. For larger scale assessments, the use of an area factor is therefore considered appropriate.

4.7. Process workflow

The methodological workflow consists of three major components: a GIS component, a database component and a code

Table 2
Impact categories for CSG infrastructure elements.

ID Impact Category	Impact description	Remarks
0	Element existed before CSG activity	As elements had already existed before CSG (e.g. existing tracks across properties) the direct spatial footprint of these elements cannot be attributed to CSG
1	Impact over lifetime of CSG production and beyond	Elements built for CSG are permanent and will not be removed after CSG. E.g. a land owner that does not wish that (a) specific access track(s) is (are) removed. Areas would thus be permanently taken out of agricultural production.
2	Impact over lifetime of CSG production only – with subsequent recovery	Elements are established for CSG production and are used over the lifetime of CSG. However, infrastructure elements will be removed after CSG and affected areas will be rehabilitated. Rehabilitated areas are assumed to not have the same productivity than before CSG but that a gradual soil recovery takes place. This gradual recovery is captured by recovery functions that are specific to soils types
3	Impact at the beginning of CSG with rehabilitation after impact	Land is accessed once to establish CSG infrastructure. Subsequently this land is rehabilitated and made accessible to agriculture (e.g. establishment of a pipeline including the digging of a trench and subsequent covering of the pipeline with soil). Productivity in rehabbed areas is assumed to gradually recover. The length of the impact in (yrs) can be variable
4	Impact at the beginning of CSG with subsequent repeated impacts over the lifetime of CSG	Land is accessed and used to establish an infrastructure element. Over the lifetime of CSG this land is repeatedly accessed (and therefore impacted) to maintain infrastructure; for instance lease areas which need to be repeatedly accessed for a well work over.

Table 3
Impact categories associated to distinct infrastructure elements.

Infrastructure elements	Impact category
Access track	1
Borrow pit	2
Camp	2
Flowline	3
GPF	2
Laydown	2
Pipeline	3
Pond	2
Dam	2
Stockpile	2
WTF	2
Lease area	4
Hardstand area	2
Vent	2

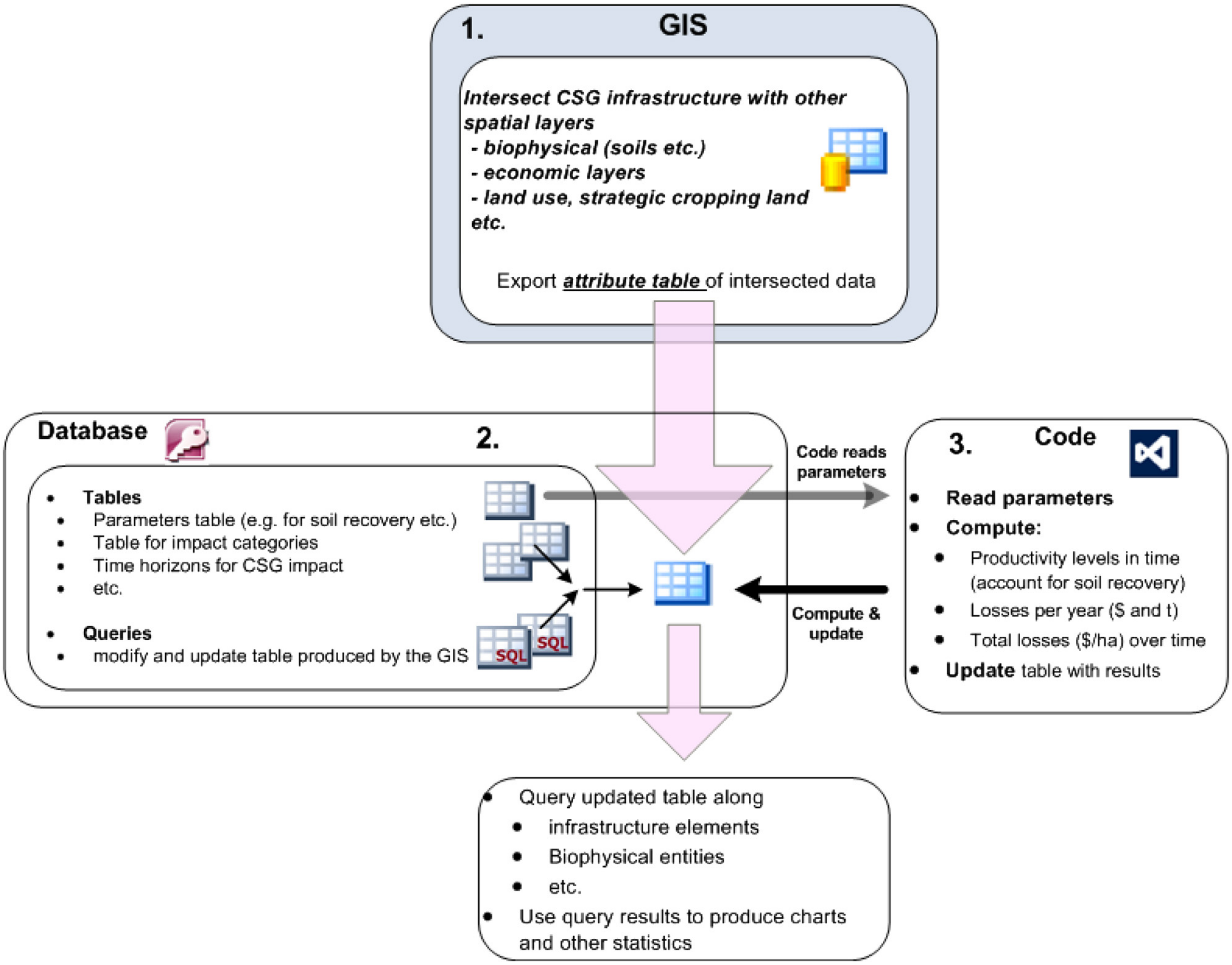


Fig. 8. Principle of the applied workflow showing the succession of the individual modelling steps.

component. The individual steps of the modelling workflow are shown in Fig. 8.

The GIS component involves a train of spatial operations on the digital layers, predominantly intersect operations where CSG infrastructure is spatially intersected with administrative, biophysical and economic layers. Spatially intersecting features basically means that target features are broken apart along spatial boundaries that intersect with the target features while attributes are simultaneously carried over. Thus, while the total spatial extent of target features does not change, the representation of these features in the GIS changes in that, when being broken up, the number of features increases. Fig. 9 depicts the principle of a spatial intersect using one access track or road feature that goes across two soil types and two land uses. While the non-intersected feature is represented by one record, the intersection along soil types and land use turns the road into three features (and therefore 3 records in the attribute table). Because attributes are carried over it is possible to link information that is specific to parts of the original feature only. For example the soil recovery functions applied can vary from part to part, depending on which soil type a specific part is located upon. Note also that economic returns associated to parts will vary depending upon the land use.

As a result of the GIS operations a feature dataset is produced which represents the CSG infrastructure that is intersected by all biophysical/administrative layers listed in Table 1.

The database component accesses and manipulates the attribute table of the intersected dataset. This involves a set of queries which add a range of new fields to the attribute table but also populate these newly added fields with two sets of information: 1) economic information that is relevant to the land use associated to each infrastructure part but also with 2) default values that are provided in parameter tables such as, for example, a default impact category ID associated to infrastructure elements. Finally, a code component accesses the database to compute impact profiles that account for the soil type that the infrastructure is located upon. The impact assessment rationale is that the soils on impacted areas will have, once rehabilitated, a productivity that is reduced relative to its original pre-CSG productivity (see Section 4.4). This reduction of productivity is highest initially but will diminish in time. This is captured by recomputing a new productivity level for each year over the period of CSG production.

The projected financial losses to agriculture that can be attributed to CSG infrastructure cannot however just be added up over the lifetime of CSG but are provided as discounted values. To obtain a sense of sensitivity for the discount rate four scenarios were run that were based on discount rates of 3%, 5% 7% and 10% respectively.

4.8. Non generic impacts at distinct infrastructure elements

When assigning impact signatures to infrastructure elements or to parts thereof, the model uses generic defaults which are defined in a database table. That is an impact signature associated to an infrastructure element is applied across all elements of the same

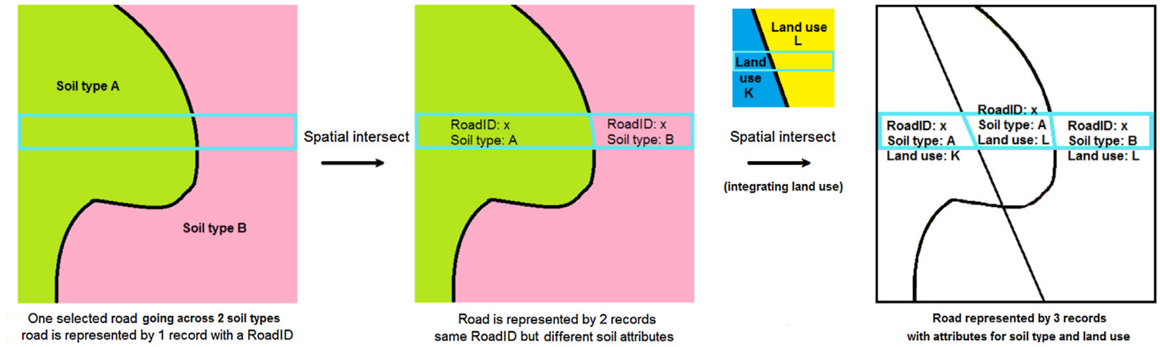


Fig. 9. Break-up of one road type feature along soil types and land use through a spatial intersect. Note that attributes are being carried over to the features that are broken-up.

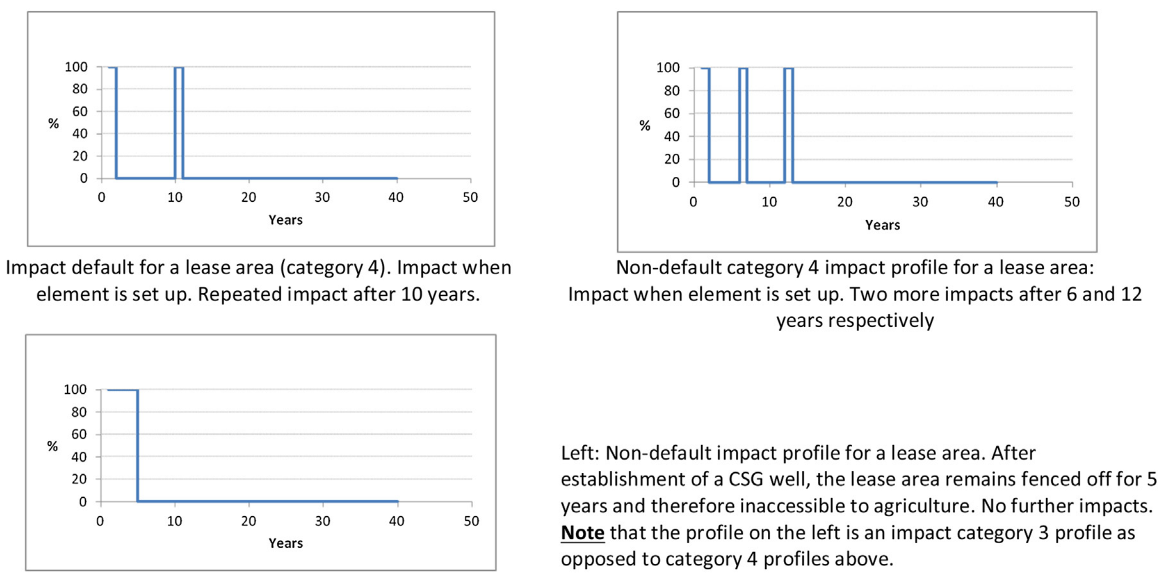


Fig. 10. Schematic example of potential impact profiles for a lease area.

kind. This generic approach is certainly a simplification but by changing default values and re-running an evaluation it will provide order of magnitude values of the range of the potential impact of CSG on agro-economic indicators within the region analysed. A higher accuracy can be achieved when specific impact signatures can be associated to individual infrastructure elements of one kind (e.g. two neighbouring lease areas could have a different number of well work overs and would have different impact profiles accordingly, see Fig. 10). Technically this is already implemented. But with the model being a predictive impact assessment model the impact frequencies for distinct infrastructure elements (e.g. the number of work overs for a particular well) would have to be known in advance. As each well in production can have very distinct production characteristics the number of work overs is impossible to predict with greater accuracy. The integration of production data as observed by CSG producers, e.g. an estimate of the average number of wells that need to undergo several work overs within a specific geologic environment, would be helpful and improve the accuracy of range of the model outputs.

4.9. Potential impacts caused by CSG not considered in the model

CSG production has a direct impact on agriculture in that CSG infrastructure takes areas out of agricultural production. However, there is a range of additional factors related to CSG extraction which impact agricultural productivity. These include for example impacts on farming operations. The presence of CSG infrastructure can make it more difficult for farmers to access part of their properties at some point in time. Besides, the potential need to navigate around CSG related obstacles can prevent the optimal use of farming equipment thus making operations more time and resource (e.g. fuel) intense and therefore more costly.

Other off-site impacts include increased dust generation along access tracks where dust particles that settle within a corridor along these tracks can reduce photosynthesis and subsequently plant growth, quality and ultimately yield (McCrea, 1984; Farmer, 1993). While CSG related traffic and therefore dust generation is highest during construction traffic is much less once CSG production wells are operational. To keep dust emissions as low as possible, CSG producers have established management rules (e.g. speed limits) however dust generation cannot be entirely avoided. Another off-site impact related to CSG infrastructure that is not covered by the model described in this paper are changes to the surface run-off and subsequent changes in erosion patterns which can lead to larger amounts of eroded fertile top soil and increased deposition of the eroded material elsewhere which can also locally impact agricultural production.

Two further potential risks that can impact on agricultural productivity include the risk of spills and leaks as well as a transfer of weeds due to an increased amount of traffic across the network of access tracks. While spills and leaks are most likely point events that are constrained to smaller areas the transfer of weed has the potential to affect and impact large areas. CSG companies try to reduce these risks through a series of management procedures

Table 4
Parameters of the model that are (or can be) subject to variation.

Parameter	Value(s) applied	Remarks
length of the CSG production period per well	20 yrs	Applied across all wells
Soil recovery function	linear	Applied across all soil types
Soil recovery time	5 yrs, 20 yrs	5 years for a rehabilitated soil having 90% of a soil's original productivity; 20 years for a highly impacted non-rehabilitated soil having 50% of a soil's original productivity
Productivity of soils in impacted areas	50%, 90%	Values taken from Antille et al. (2014)
Number of impacts in lease areas	2, 5 and 15	# repeated impacts due to well work-overs
Area impact factor	5 for pipeline vents 1 for all others elements	To capture the fact that farmers have to navigate around obstacles in the field a factor of 5 was applied to the nominal area of pipeline vents. In grazing areas a value of 1 was applied for vents
Discount rate	3%, 5%, 7% and 10%	Discount rate applied to compute the present value over a 20 year production period (plus a post CSG phase). Present value is in 2011 Dollars

including a) the strict application of relevant standards and the use of in-vehicle monitoring systems (spills) and b) a strict application of procedures including vehicle wash procedures, training of staff and vehicle inspections (weeds). While a potential residual risk is likely to exist, associated impacts on productivity are not yet integrated in the model. Therefore the model currently underestimates these full impacts of CSG on production.

5. Analysis

5.1. Parameter uncertainty

There is a variety of parameters used in the analysis that are difficult if not impossible to predict or that require additional data that are not available with any accuracy. Due to this lack of knowledge there is some uncertainty around some of the parameters that are part of the model (Table 4). To obtain an understanding of the range of the impact on agro-economic returns a set of 24 scenarios using a range of different combinations of the parameters listed in Table 4 were modelled. The combinations of parameters are given in Table 5.

It was furthermore assumed that no access tracks had existed before CSG activity started. This means that all current tracks had to be established for CSG. It is however common practice that CSG producers try to minimise the spatial footprint and use existing tracks when possible. A time series of satellite images (going back to the year 2002) of the study area was analysed in Google Earth where roads and tracks of older imagery was compared to the current network of access tracks. As a result of this analysis it can be concluded that 10% of the access track network had existed before CSG activity started. Therefore the impact of access track parts on agro-economic returns needed to be multiplied by a value of 0.9.

In regards to the number of well work overs, it has to be noted that a workover of a well is expensive. CSG producers will avoid spending more on workovers than a well generates in revenues. Therefore it is more likely that the number of workovers will be small rather than large. To simulate some more permanent impact on the lease areas a maximum number of 15 repeated impacts was chosen to be added as a scenario though. This was based upon field observations that indicated that some lease areas were not going to be made available to agriculture for a longer period in time (some lease areas were highly compacted and had a pebble surface, whereas others were fenced etc.). Alternatively, an impact category 3 could be assigned with the length of the initial impact set to 20 years (=making that impact last over the life time of CSG).

In relation to the soil types and associated parameters it has to be noted that the soils were classified into three broad generic soil classes (Vertosols, Sodosols and Tenosols). It can be assumed that during the construction of infrastructure elements of one kind machine equipment and therefore loads imposed on soils are similar. However, depending upon the magnitude of the impact, the soil type, its texture, soil conditions at the time of impact (e.g. water content), climate, post-impact management practices applied (i.e. controlled traffic and agronomic practices) and quality of the rehabilitation soils may show a different recovery response. Soil recovery rates (years) are therefore hard to predict and the number of years provided in Table 4 are to be considered estimates based on an yearly recovery rate equal to a yearly yield improvement between 2% and 3%. The model allows for a change of these parameters any time and model results will be updated accordingly.

5.2. Results

Fig. 11 shows the losses to gross revenues associated to distinct CSG infrastructure elements with soil productivity levels reduced to 50% and 90% respectively. The present value for the revenue losses was computed using discount rates of 3%, 5%, 7% and 10% (Table 5). The magnitude of the loss associated to a distinct infrastructure element is related to the size of its spatial footprint and the duration of the impact. Losses are generally lower in scenarios where soils were considered to have been well rehabilitated. Repeated access due to maintenance works was only assumed for the lease areas. Therefore it is only the lease areas that, with an increased number of impacts, "move" upward on the charts.

Table 5
Combination of parameters for distinct scenarios.

Parameter	# scenario																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Productivity of soils in impacted areas (%)	50	50	50	50	50	50	50	50	50	50	50	50	90	90	90	90	90	90	90	90	90	90	90	90
Soil recovery time (yrs)	20	20	20	20	20	20	20	20	20	20	20	20	5	5	5	5	5	5	5	5	5	5	5	5
Number of impacts in lease areas (−)	2	2	2	2	5	5	5	5	15	15	15	15	2	2	2	2	5	5	5	5	15	15	15	15
Discount rate (%)	3	5	7	10	3	5	7	10	3	5	7	10	3	5	7	10	3	5	7	10	3	5	7	10

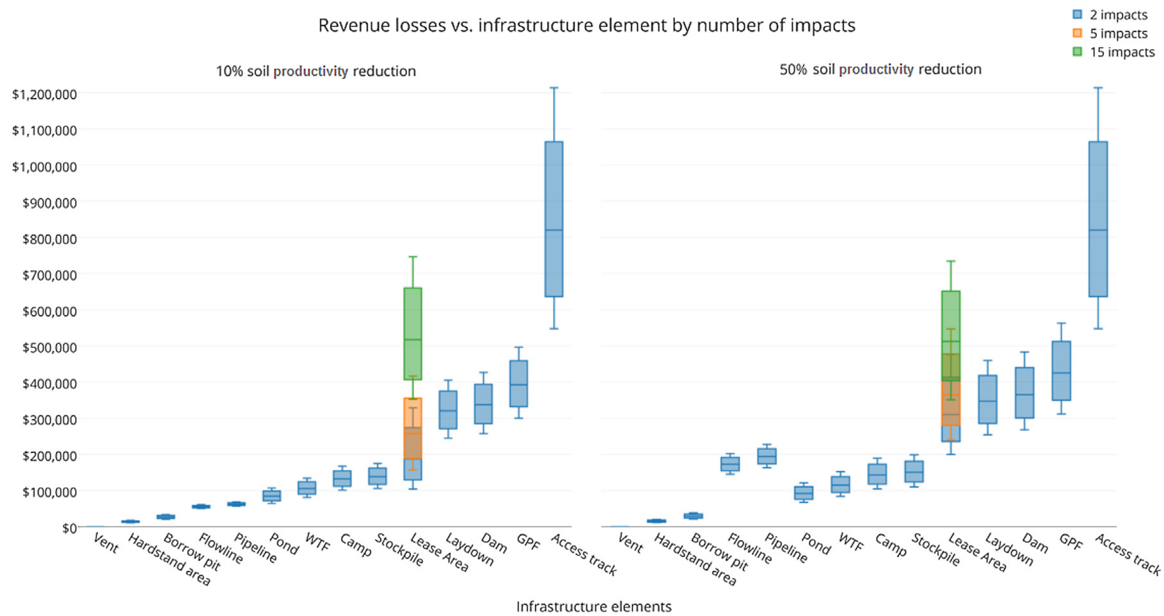


Fig. 11. Range of present values (reference year 2011) of the losses to agricultural revenues due to the presence of infrastructure elements. A reduction in soil productivity by 10% (=90% of original productivity, left) and 50% (right) is assumed. The spread in values is caused by different discount rates (3%, 5%, 7% and 10%).

Table 6
Estimated min, max and average losses to agricultural revenues ($) in the study area (present value – year 2011 ($)). Size of study area is 11,500 (ha). Area of infrastructure is 920 (ha) which equates to some 8% of the study area. 155 CSG wells included.

	Loss of revenues (discounted $)	% of losses of the total revenue in study area
Average	2,174,752	7.21%
Min	1,321,428	4.38%
Max	3,292,046	10.92%

It should be noted that other elements for example pipeline sections may need to be accessed for repairs/maintenance as well. It is however not possible to predict where these works might occur, how large the affected area would be or if there is a need to repeatedly access a pipeline section for repairs. Due to the lack of this information repeated impacts on elements other than lease areas where not included. The total number of wells that was included in the analysis was 155.

In the scenario assessment the total losses to gross revenues incurred by the existence of CSG infrastructure varied between $1.32 m and $3.29 m and averaged $2.17 m (Table 6). These values are based upon the set of 24 scenarios. Access tracks and lease areas contribute most to economic losses (Fig. 11). While the impact of the dam, the gas processing plant and the water treatment facility are large as well, these facilities will serve not only existing wells but future wells within and beyond the study area. Therefore the current relative contribution of these larger infrastructure elements is comparatively higher now than in the future.

The standard CSG well spacing is 750 m. This standard raster is often slightly varied for a variety of reasons such as ease of access or as a result of negotiations with land owners who wish wells to be slightly shifted. With an average well spacing in the study area of about 800 m the wells do not follow a perfect 750 m raster spacing. However, based upon the standard well spacing, a standard area of 56.25 (ha) (=750 m × 750m) was defined around each well. All infrastructure elements within this area were then associated to the central well of a standard area. This allowed for an assessment of the spatial footprint and the economic losses per well.

Fig. 12 shows the area of CSG infrastructure that can be attributed to individual wells. Some 70% (=106) of the wells have a fairly uniform area impact between 1.4 (ha) and 5 (ha) (see Point A on Fig. 12). These are "standard wells" in the field without any major infrastructure elements nearby. Beyond Point A the areas associated to wells increase steadily up to 10 ha and climb steeply thereafter. This increase in impact area is caused by the proximity of wells to other major infrastructure elements such as a dam or the gas and water treatment plants. With these elements close by the area footprint per well increases significantly.

Table 7 shows the average areas (ha) impacted by infrastructure and average revenue losses for wells grouped by land use.

With the evaluation system being spatially explicit area impacts (ha) and losses in revenues ($) can also be attributed to various spatial entities, for example portions of the study area that are mapped as strategic cropping land (SCL); land which is considered strategic due to its high agricultural value. Fig. 13 shows that 43% of the CSG infrastructure in the study are on SCL but losses on SCL contribute to 71% to the total losses. The bottom of Fig. 13 shows the distribution of the area impacts and revenue losses associated to CSG elements across the three major soil types in the area. Vertosols are the dominant soil type covering some 60% of the study area but about three quarters of the losses occur on Vertosols. The losses in gross revenues ($) Fig. 13 refers to are based on the average scenario (see row 1, Table 6).

6. Discussion and conclusions

We have presented a new approach that facilitates the assessment of the economic impacts of large scale CSG infrastructure on agriculture. Being linked to a GIS the approach allows for the provision of estimates of losses of gross economic returns for a variety of spatial entities.

The presented system accounts for impact typologies of individual CSG infrastructure elements, the quality of rehabilitation measures and the recovery capacity of soils after compaction. Linking this information to economic data allows to establish a more detailed picture of revenue losses to agriculture that can be attributed to individual infrastructure elements. The largest impact footprints are caused by flowlines, lease areas, a dam, access tracks

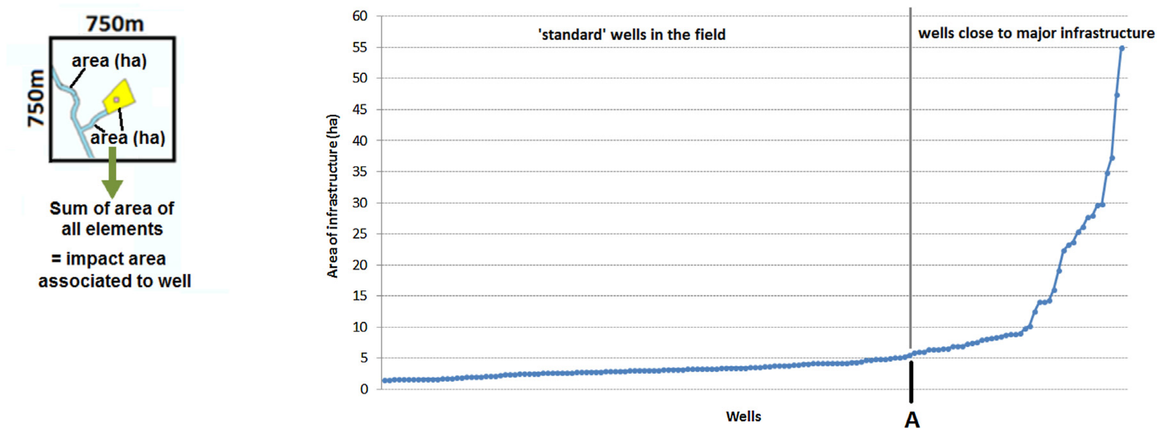


Fig. 12. Area (ha) of infrastructure that is located within a 750 m × 750 m square around each well.

Table 7
Average areas of infrastructure and average losses to gross revenues associated to CSG wells in the study area. Losses to revenues are expressed as the present value with the reference year 2011. Time frame considered is 20 years (plus post CSG phase).

Well type	Land Use	avg. impact area (ha)	Discount rate (%)	avg. revenue loss ($ present value)	# wells values are based upon	Remark(s)
Standard well <5 ha	Cropping	2.79	3	15,880	12	7 wells where 100% of infrastructure elements are in cropping, 5 wells >90%
			5	12,107		
			7	9684		
			10	7438		
Standard well <5 ha	Grazing	2.88	3	3027	59	Only wells included where >99% of all infrastructure elements are in grazing
			5	2310		
			7	1848		
			10	1420		
Standard well <5 ha	Grazing and cropping	3.01	3	6684	106	
			5	5102		
			7	4086		
			10	3142		
all wells	Grazing and cropping	7.00	3	15,309	155	Includes wells proximal to major infrastructure elements such as a gas processing plant and a water treatment facility
			5	12,207		
			7	10,094		
			10	8003		

and the main pipeline (Fig. 4) however it is the access tracks that are to be associated with the largest revenue losses; areas affected by pipeline elements suffer comparatively lower losses. The reason is that access tracks take land out of production to 100% over the whole lifetime of CSG and therefore incur revenue losses of 100%. Pipeline areas undergo one impact during the establishment phase after which these areas are accessible to agriculture again. Even though the spatial footprint is large, losses on these areas are therefore much lower. It cannot be excluded though that some pipeline sections may need to be re-accessed for repairs. It is however not possible to know where, when and how often this would happen. There are however areas of infrastructure where it is highly likely that they will be repeatedly accessed: the lease areas which will be impacted when a well requires a work over. As it is unknown at this stage how many works over will be required at a particular well site over its lifetime a scenario approach using a varying number of workovers across all lease areas was applied. The impact of different work over counts on losses to revenues was monitored and losses on lease areas can eventually exceed the losses attributed to access tracks if the number of workovers is high.

The footprint that needs to be associated to a CSG well goes well beyond the size of a well pad and its associated lease area. The footprint that needs to be attributed to a "standard well" (Fig. 12) ranges from 1.4 to 5 ha and has an average of about 2.7 ha. An analysis which aggregated all revenue losses associated to individual wells revealed average revenue losses in cropping between $7,500 and $16,000 per standard well whereas the average losses in grazing ranged between $1,400 and $3,000. The losses on grazing land due to CSG impacts do not explicitly take into account impacts related to changes to the above and below ground biomass which take time to establish after rehabilitation. Doerr et al. (1984) analysed grass re-growth over a 5 year period applying 4 different (low to severe) soil disturbance treatments and found a negative correlation between grass production and intensity of the soil disturbance. We attempted to account for different qualities of rehabilitation measures by using different reduction rates of productivity (10% and 50%, respectively) and different length of the recovery rates (5 years and 20 years respectively). The efficacy of the rehabilitation measures applied by the CSG producers and the establishment of the below ground biomass will have to be verified through field studies in the years to come. It is acknowledged though that the determination of the below-ground biomass is considered difficult which is why below ground biomass is often estimated as a portion of the above ground biomass (Ravindranath and Ostwald, 2008).

All presented Dollar values are present values of the year 2011. With ($/ha) revenues generated on grazing being lower than in cropping the differences of results for cropping and grazing are not too surprising. However the figures provide the first tangible modelled estimates of average losses to gross revenues on agricultural land caused by CSG infrastructure.

It should be noted that the land on which major infrastructure elements such as the water and gas treatment plants as well as dams and ponds reside is owned by the gas company. The authors assume that, for legal and logistic reasons, gas companies would tend to

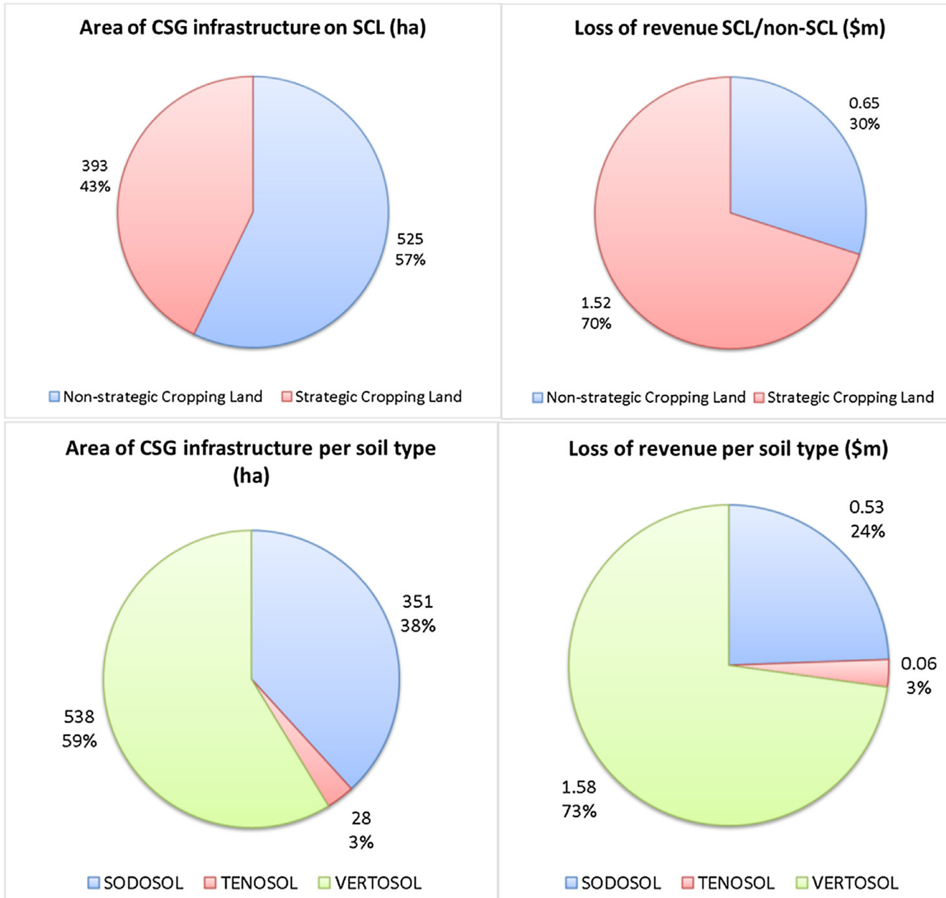


Fig. 13. Footprint and revenues losses attributed to CSG infrastructure in different spatial entities. Top: strategic cropping land (SCL). Bottom: soil type.

buy, rather than rent the land on which these crucial infrastructure elements are built. It should also be noted that impacts of CSG at a well site do not come to an end with the decommissioning of a well. Even if areas are rehabilitated after CSG production it will take time for a soil to come close to its original productivity potential. To capture soil recovery occurring after the main CSG phase, a "post-CSG" phase was included in the model also.

6.1. Uncertainty

Impacts of spatial uncertainty are hard to quantify. It is assumed that the spatial datasets used, both industry and government datasets, have been compiled with the greatest accuracy possible. For a larger scale assessment we therefore assume that an error introduced by mapping inaccuracies would be minor. However, if a small scale, farm size assessment, was to be made the accuracy of mapped entities should be checked by field visits. To accommodate uncertainty of some model parameters a scenario based approach with upper and lower parameter bounds was applied. This includes uncertainty around the soil recovery which is linked to the magnitude of soil compaction at the time of impact and the quality of the rehabilitation. To capture the potential range of productivity impacts, two productivity impact scenarios applying a post impact productivity of 50% and 90%, representing an inferior (or non-rehabilitated) and a favourable rehabilitation scenario, respectively. The number of work overs per well is currently unknown. CSG operations in the study area are relatively recent and there is limited experience available as to how many work overs per well will be required on average. The model inputs can be refined through the incorporation of knowledge that will be gained through CSG operations in time, knowledge which CSG operators would have to share.

The economic information sourced from the ABS is provided for statistical entities and not for individual enterprises or biophysical entities. As such the economic data used in this study are generically applied within the outlines of these statistical entities which introduces some inaccuracy. Uncertainty related to fluctuations in revenues over time was accommodated by using average revenues for specific commodities that were reported over a period of 20 years. To gain an understanding of the sensitivity of the discount rate, scenarios based on four different discount rates were applied.

The employed scenario based approach provided insight into the range of the losses of agro-economic returns in the study areas caused by CSG activity.

6.2. Aspects not included in the model

There are a variety of aspects the developed model does not account for. These include an increase in dust generation, changes to the surface runoff and questions of inconvenience to farmers. The increase of dust is caused by an increased amount of vehicles travelling along access tracks and nearby public roads. The fine particle matter will settle on the plants alongside an access track corridor and thus impact on photosynthetic activity and ultimately on plant growth and production. It needs to be mentioned though that traffic reduces significantly once wells are in operation. Due to the presence of the CSG infrastructure the surface hydrology is changed also which leads to changes in erosion and the depositional pattern within the areas affected and potential subsequent impacts on agricultural production. The establishment and operation of CSG infrastructure comes with a variety of inconveniences to the farmers also. These include navigation around obstacles such as signs, pipeline and vents, to name a few. These manoeuvres take more time, take more fuel and can locally lead to higher soil compaction. Another factor which is not accounted for is the time that farmers spend in negotiations with CSG companies which in turn can reduce productivity as well (Commonwealth of Australia, 2015). However there is potential to offset these productivity reducing factors through compensation and access to, as a by-product of CSG production, treated water (Commonwealth of Australia, 2015; Towler et al., 2016). Principles for negotiating appropriate co-existence arrangements are provided by Clarke (2013).

6.3. Concluding remarks

We presented an original model to provide estimates of economic losses to agriculture caused by mining operations on a large scale. The estimated values for impacts per well both in terms of area and losses to agricultural revenues can be used to infer impacts on a grander scale. The transfer of economic values to areas further inland would require some adjustments though as the areas further away from the Australian east coast receive lower amounts of rainfall. Conversely, a transfer of the estimated economic losses to areas closer to the wetter coast, where agricultural returns tend to be higher, would require an adjustment also. With grazing being the dominant land use in the study area losses will significantly go up if an analysis was undertaken in areas where non-livestock agriculture predominated (e.g. cropping or irrigated agriculture).

The model developed is transparent and flexible. Parameter values can be changed, subsequent impacts on results can be monitored and the method can be applied in other geographic areas as well. Links to a GIS facilitate the targeting of different spatial scales. However, the data used by the model are not equally accurate across all scales and were predominantly produced for larger scales: regional, state and national scale. If small scale assessments at a farm level were to be made we caution the use of large scale data and recommend using farm scale data.

At this stage the model is run using a suite of different software packages (a GIS, a database and a code component). An online platform could be developed to provide farmers or communities with access to spatial layers and estimates of revenue losses.

The provided estimates represent present values ($) of CSG related losses to gross economic returns caused by taking agricultural land out of production. With the year 2011 being the reference year the provided estimates represent the value of lost production over the lifetime of CSG as valued in 2011. The authors would like to stress that the estimated losses to gross revenues must not be equated to compensation payments. Compensation will have to account for a whole range of additional factors that capture the impacts of CSG on farming operations (see for example Clarke, 2013; Commonwealth of Australia, 2015); lost productivity as covered in the presented analysis is an important factor but just one factor out of many.

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