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Scenarios for shale gas development and their related land use impacts in the Baltic Basin, Northern Poland

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HIGHLIGHTS

- A range of scenarios for shale gas development in Poland were modelled.
- The impact in terms of land take and competition for land was assessed.
- Of land used for industrial purposes, 7–12% was attributed to shale gas extraction.
- If unregulated, 24% of well pads were developed within protected areas.
- The legislative framework can have a major influence on overall environmental impact.

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ABSTRACT

Scenarios for potential shale gas development were modelled for the Baltic Basin in Northern Poland for the period 2015–2030 using the land allocation model EUCS100. The main aims were to assess the associated land use requirements, conflicts with existing land use, and the influence of legislation on the environmental impact. The factors involved in estimating the suitability for placement of shale gas well pads were analysed, as well as the potential land and water requirements to define 2 technology-based scenarios, representing the highest and lowest potential environmental impact. 2 different legislative frameworks (current and restrictive) were also assessed, to give 4 combined scenarios altogether. Land consumption and allocation patterns of well pads varied substantially according to the modelled scenario. Potential landscape fragmentation and conflicts with other land users depended mainly on development rate, well pad density, existing land-use patterns, and geology. Highly complex landscapes presented numerous barriers to drilling activities, restricting the potential development patterns. The land used for shale gas development could represent a significant percentage of overall land take within the shale play. The adoption of appropriate legislation, especially the protection of natural areas and water resources, is therefore essential to minimise the related environmental impact.

1. Introduction

OECD-Europe accounts for roughly 5% of global conventional natural gas reserves according to the latest outlook published by the International Energy Agency IEA (2014). The IEA also projects an annual average decline of 1% in the production of natural gas in Europe as a whole between 2012 and 2040, thus making it increasingly reliant on imported resources (IEA, 2014). This projected trend is supported by production statistics recently published by oil and gas companies (ENI, 2014; BP, 2014). In combination with increasing domestic energy consumption this has led to rising energy prices and security of supply concerns. There is therefore increasing interest in unconventional energy resources, amongst which shale gas has garnered particular attention over the last few years.

In the US, shale gas was first extracted by hydraulic fracturing in the mid-60's (Ray, 1976), and the industry has grown

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significantly ever since. Shale gas accounts for some 30% of the nation's natural gas reserves (USDE, 2011), and has become vital to the security of domestic energy supply. Even though there are no European countries among the 10 with the highest technically recoverable shale gas resources in the world (Melikoglu, 2014), resources in Europe may also play an important role in fulfilling the gas demand, and are currently being explored in several countries (Pearson et al., 2012).

Even though there is a push to try and replicate some of the economic successes of the US, the situation in Europe on the topic remains volatile. At this point in time hydraulic fracturing is banned in France, the Netherlands, and Luxembourg due to concerns on the environmental impacts involved. Higher population densities, a more challenging geological situation (shales generally lie deeper), and a more regulated market, together with the availability of technology infrastructure, also suggest that the development of shale gas as a resource in Europe may not progress so smoothly (see, as examples, Asche et al., 2012 and Selley, 2012, in Sovacool, 2014). For most European countries there is also as yet no specific legislation, and the regulations in place for conventional gas are assumed.

At the time of writing there was still no unified EU policy on the utilisation of shale gas resources (Melikoglu, 2014), even though both general and specific parts of European environmental legislation apply. In order to counteract an increasingly diversified operating framework among different Member States, the European Commission is developing a basic level of regulation for all EU countries. After two resolutions were adopted by the European Parliament in November 2012 (EP, 2012a,b), the need for a coherent framework at European level led to the adoption in 2014 of a Recommendation on"minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high volume hydraulic fracturing in the EU" (EC, 2014a). This Recommendation was accompanied by a Communication outlining the potential opportunities and challenges stemming from shale gas extraction in Europe, as well as an Impact Assessment focused on the socio-economic and environmental impacts of various policy options (EC, 2014b,c).

Shale gas is exploited by (1) horizontal drilling of Shale beds to increase borehole contact with the shale and (2) high-volume hydraulic fracturing (fracking) of the shale surrounding boreholes to enable migration of the gas through the shale (King, 2012). Fracking involves high pressure pumping of fluid into the formation, in order to produce hydrofractures which propagate through the surrounding shale.

There are several environmental concerns involved with this extraction procedure, including impacts on water and air quality, noise and visual pollution, potential impacts on biodiversity and nature conservation objectives, and even seismic triggering (NYSDEC, 2011; Rutqvist et al., 2013; Gény, 2010). Since the development of shale gas resources requires extensive drilling across large areas, competition with existing/alternative land uses is also of concern (Racicot et al., 2014). Besides causing visual pollution, the actual take of land for shale gas exploitation may have serious and lasting impacts on the landscape, especially in densely populated areas (Wood et al., 2011). The composition of the fracking fluid used is not often publicised, but predominately consists of fresh water combined with sand and a variety of chemical additives, some of which may be toxic (Centner, 2013).

In this paper we focus on developing a methodology to simulate the extraction of shale gas by hydraulic fracturing over time, in order to analyse the possible impacts it may have on the landscape and understand the influence of legislative restrictions. Specifically, we aim at answering the following questions for our study site in Northern Poland:

- *What are the aggregate land-use requirements associated with shale gas development?*
- *What are the associated land-use conflicts, including competition with alternative land uses?*
- *What impact could legislative constraints have on the land take for shale gas development?*

We reviewed the current available literature in order to identify the variables that most influence the land requirements associated with shale gas development. We also looked into the current legislation in place on shale gas both in Poland and the US. We then derived a range of representative values spanning worst- and best-case scenarios (in terms of environmental impact) for each variable. On this basis, we defined 2 specific technology scenarios and 2 legislative scenarios for shale gas development in Northern Poland for the period 2015–2030.

These scenarios were run using the land-use model EUCS100 (Lavalle et al., 2011a) to assess the quantity of land necessary for shale gas extraction and the spatial distribution thereof. Shale gas extraction sites (well pads) were modelled as a separate land-use class, with its own specific requirements and allocation rules. This paper follows on a literature review (Kavalov and Pelletier, 2012), and previous modelling exercise (Lavalle et al., 2013). The impacts on water resources for the scenarios developed here are further discussed in Vandecasteele et al. (in press).

1.1. Study area

The study area covers 11,313 km^2 within the Baltic Basin in Northern Poland. Poland is currently one of the most active EU member states in exploring its shale gas resources, with estimates ranging from 23 to 1549 Bcm (PGI, 2012; EIA/ARI, 2013). To date some 40 exploratory wells have been drilled (Uliasz-Misiak et al., 2014). Fig. 1 shows the location of our study area, as well as the current shale gas concessions and exploration wells throughout Poland.

The study area was defined based on data availability and the thickness, depth and thermal maturity of the shale deposit (Fig. 2, derived from PGI, 2012). This site was already identified as particularly suitable for development in Lavalle et al. (2013).

As detailed in Table 1, the predominant land uses within the shale play area are arable land and forest, which occupy respectively some 56% and 28% of the total shale play area. Other uses, such as permanent crops, pasture land, and semi-natural vegetation are scarcely represented. The area is predominantly rural, even though there are larger urban areas, such as the city of Gdansk. There are also several areas protected under European and National schemes within the study site, namely Natura 2000 sites and Nationally Designated Areas. Together these account for 22% of the shale play area.

1.2. Data availability

Although the issue of potential shale gas development in the EU is receiving considerable attention, to date only a relatively small number of exploratory drilling activities have been undertaken. There is hence little available information at present on which to base EU-specific technology scenarios. Consequently, we based our scenarios on the best data available from the literature, using in as far as possible Polish data. Where sufficient information was not available we assumed data derived from the longer-running US shale plays (e.g. Marcellus and Barnett plays) to give a reasonable estimate, especially in the case of factors affecting the well placement and development rate.

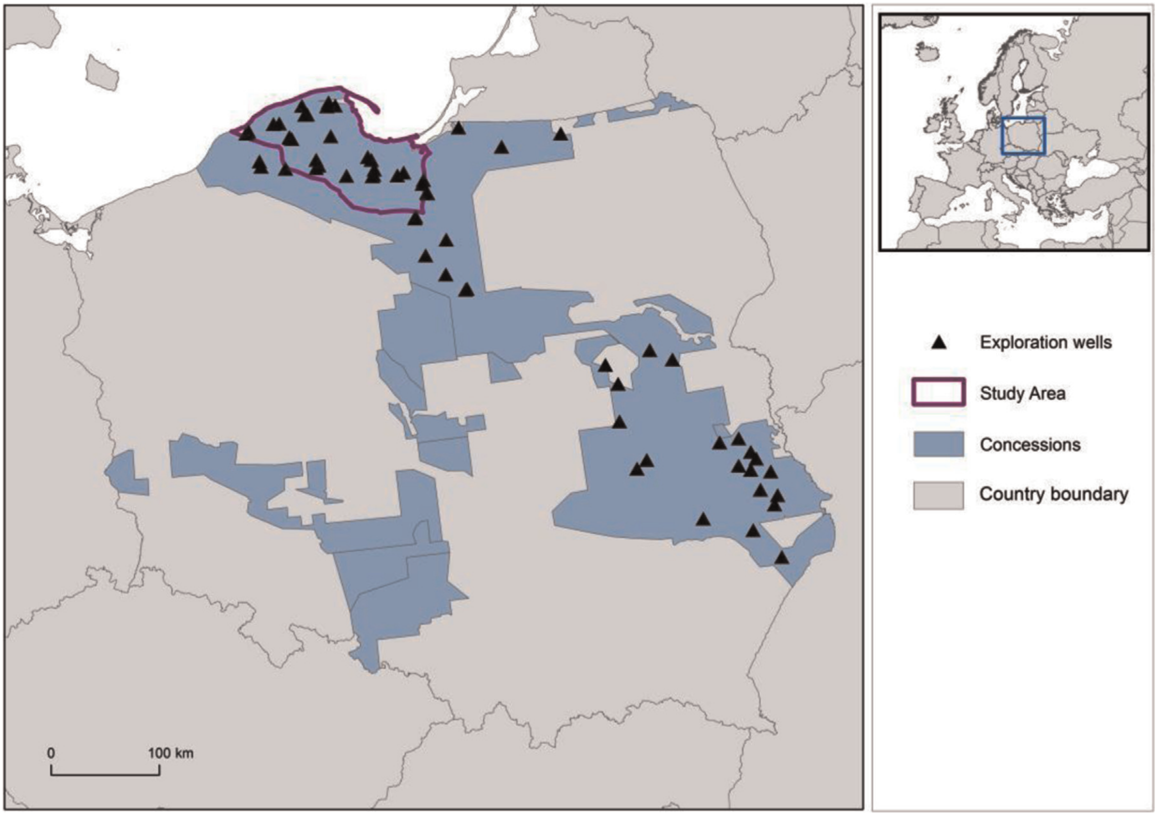

Fig. 1. Map of Poland showing the current shale gas concessions and exploration wells. The study area is located in Pomorskie region in the north of the country.

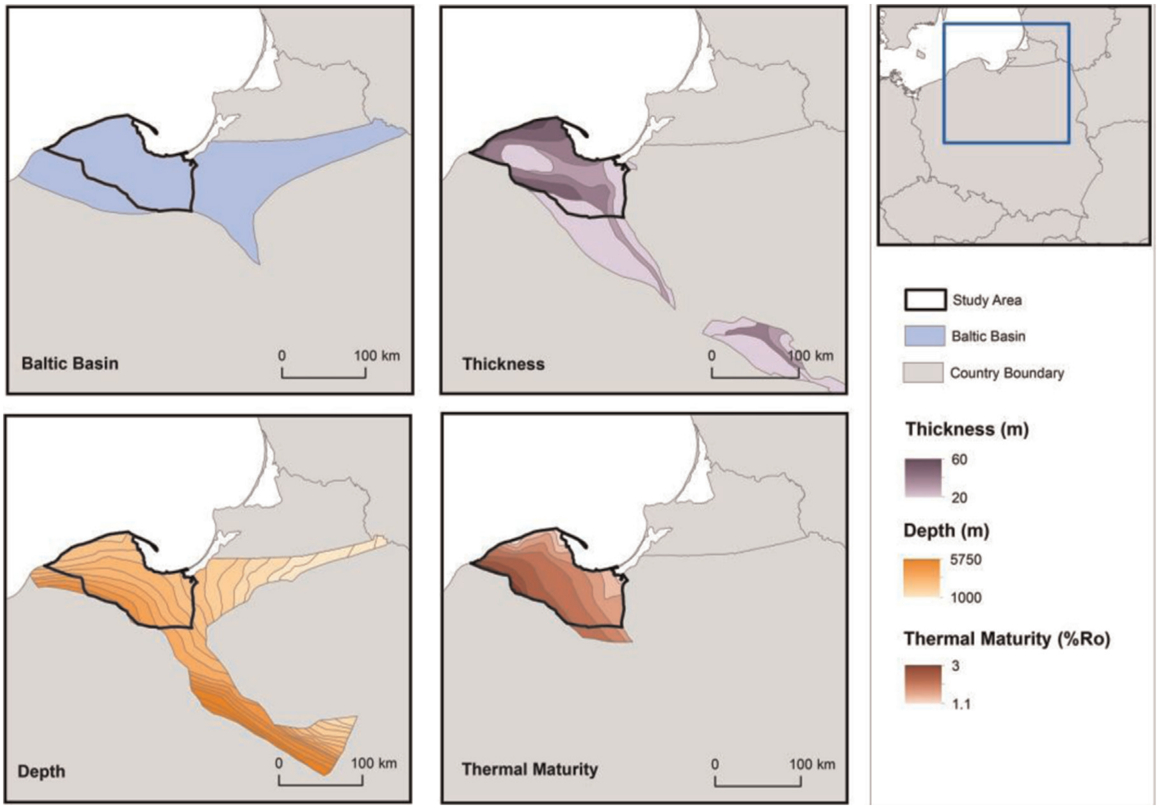

Fig. 2. Specific geological characteristics of the study area relevant to shale gas exploitation.

Table 1
Land use shares within the shale play in 2006, as per the refined version of Corine Land Cover (Batista e Silva, 2013a).

Land Use Type	Area (ha)	Percentage of land area (%)
Arable	656,620	55.8
Forests	335,738	28.5
Pastures	72,377	6.2
Urban fabric	46,467	4.0
Water bodies	35,880	3.1
Industry	8,812	0.8
Wetlands	6,865	0.6
Semi-natural vegetation	5,548	0.5
Infrastructure	5,539	0.5
Other nature	2,804	0.2
Permanent crops	1,142	0.1

2. Methodology

Several steps were involved in the modelling procedure. A “business-as-usual” land-use scenario was used for all simulations, based on historical and projected trends in demography, Gross Domestic Product (GDP), and land requirements for agriculture and forest land; and assumes that the relevant current policy provision is maintained.

We developed scenarios combining technological and legislative frameworks to describe the possible range in characteristics of future shale gas development in Poland. In addition, a Baseline Scenario was simulated where no shale gas activity was undertaken as a term of comparison for assessing relative impacts on resources. A dynamic allocation of well pads was carried out for the shale gas exploitation scenarios based on the updated Water Exploitation Index (WEI), updated suitability layer, and specific allocation settings.

The suitability layer is a map which takes into account the scenario-specific variables which either favour or restrict the placement of the shale gas well pads. This simulation was carried out for the time period 2015–2030, so as to provide insights into foreseeable impacts for each scenario over the short to medium term. The exploitation sites (well pads) were allocated every 5 years, taking into account an annual rate of development. For each allocation year (2015–2020–2025–2030), four main steps were performed.

The first step was implemented with the EUCS100 model (Lavalle et al., 2011a). Land-use changes were simulated for the entire country, starting from 2006 (base year of the model). In 2015 the simulation was stopped and the resulting land-use map was then used to compute the Water Exploitation Index (WEI), which was

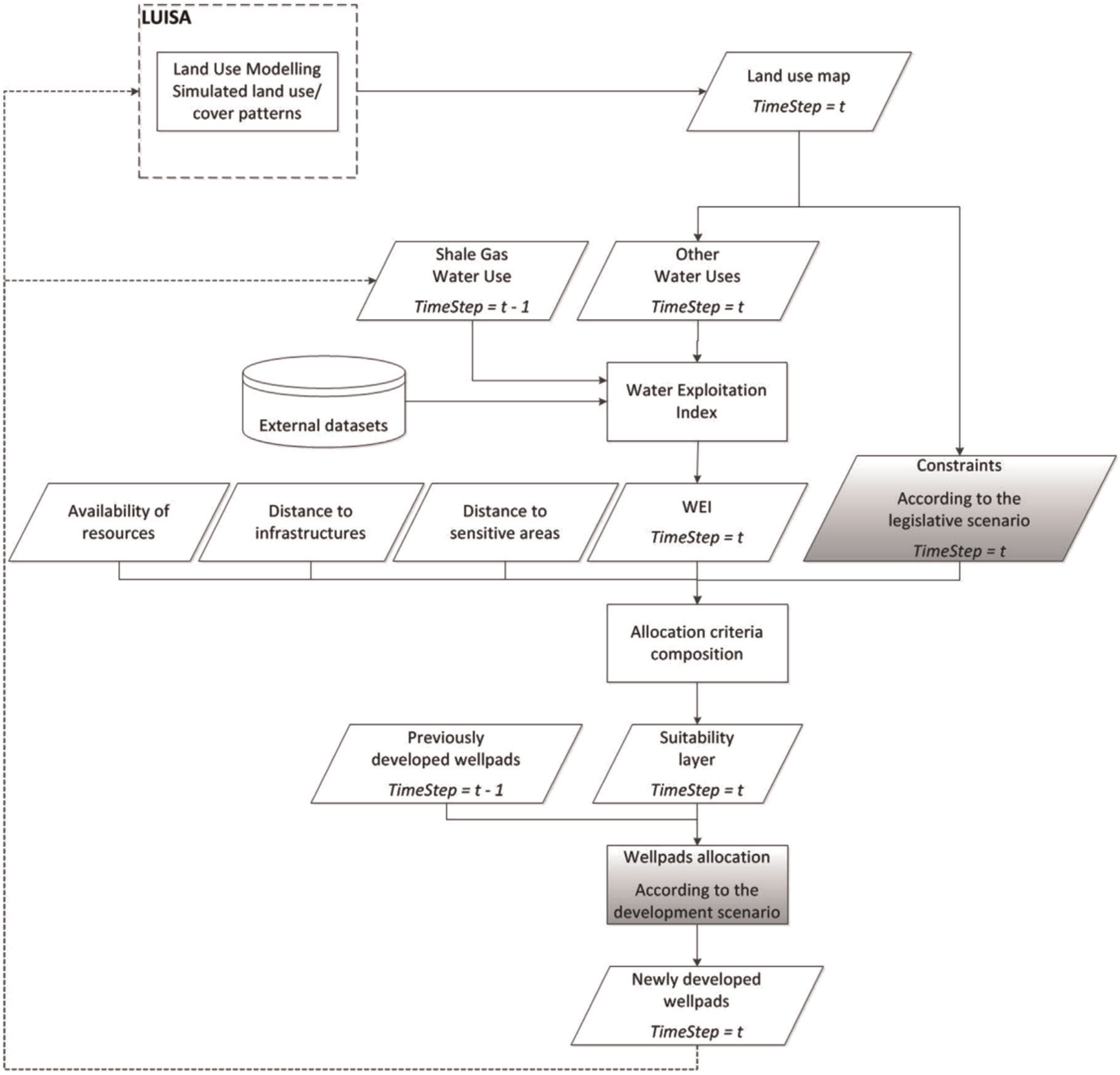

Fig. 3. Overall workflow followed for the dynamic allocation of well pads. The variables which are scenario-dependent are shaded in grey.

Table 2
Summary of the parameter values used to define the technology scenarios. The values reported within brackets represent the values as reported in Kavalov and Pelletier (2012); the values outside the brackets are those rounded off and used in the simulations.

Scenario	TLow	THigh
Construction land use per well pad [ha]	10 (9.93)	4 (3.55)
Operation land use per well pad [ha]	4 (3.75)	1 (1.06)
Lifespan per well pad [years]	10	10
Minimum distance between well pads [m]	3200	600
Water recycling scenario [%]	49%	0%
Water consumption per well [m^3]	8000	19,000

used as a measure of the water stress within each sub-catchment (EEA, 2010a). The suitability layer, which indicates the optimal locations for shale gas development, was then computed based on several data sources and both the updated land use and WEI.

Finally, the well pads were allocated based on the suitability score and a neighbourhood effect: this latter takes into account the location advantage of placing extraction sites in areas where the necessary infrastructure has already been developed for the surrounding sites. Once the well pads had been placed, the updated land-use map was fed back into EUCS100, so as to run the next 5 years of the simulation time period. The modelling steps involved are summarised in Fig. 3.

2.1. *Defining the technology scenarios*

There are numerous factors influencing the impact of shale gas extraction on land and water resources. The first and foremost is the technology used. The characteristics of the shale gas extraction wells themselves, their placement and specifications, and the actual amount of land occupied and water consumed per well are highly variable factors.

For each parameter we considered what value would have the highest and lowest relative potential environmental impact (Lavalle et al., 2013). In such a way, we defined a 'worst' and 'best' case scenario for each variable and combined them together in order to build a relatively higher, and relatively lower impact technology scenario (see Table 2). From here on these technology scenarios are referred to as THigh and TLow respectively.

2.1.1. *Shale gas exploitation rate*

There are large discrepancies among published resource estimates in Poland. We used two main sources in determining the estimated shale gas resources present in the study site.

The Polish Geological Institute (PGI) estimated the resources available within the Baltic basin (PGI, 2012). The report used well performance data from the United States Geological Survey, and applied the Estimate Ultimate Resources (EUR) methodology (USGS, 2012). The EUR is the sum of all gas expected to be produced for a single well over time, including gas which is not currently producible and resources which are expected to be discovered. This definition is sensitive to a range of assumptions on future gas prices, technological developments, and discovery rates (McGlade et al., 2012). Using these data, the estimated minimum and maximum resources of our study area were calculated based on the proportion of the study area over the total area covered by the Baltic Basin, resulting in an estimated range of 22–551 Bcm.

The U.S. Energy Information Administration (EIA/ARI, 2013) used a volumetric approach to calculate the Gas In Place (GIP). The GIP is the total volume of natural gas that is estimated to be present in a given field, play or region. This volume is never 100% recoverable; the fraction of this gas that can be recovered is estimated by the recovery factor, which can vary significantly depending on geological conditions, technologies used, and the prevailing economic environment (McGlade et al., 2012). The prospective GIP within our study area was calculated using the area proportion, resulting in estimated resources of 2311 Bcm. In order to develop our scenarios, we used the median of all the total available resources estimates calculated using the area proportion, 386 Bcm.

We assumed that 50% of these resources would be recoverable within the next 15 years, if commercial extraction were to begin in 2015. We see this as a reasonable assumption considering the early stages of development of the industry in Europe, and the short time frame of our simulation. We assumed an intermediate decline rate of production per well (0.066 Bcm/well/year, Broderick et al., 2011). Considering a constant rate of development, this results in an allocation of 37 and 294 well pads every 5 years for the TLow and THigh scenarios respectively.

2.1.2. *Land and water requirements*

The amount of land required for shale gas development will vary depending on, amongst others, the well pad density, well pad size, number of wells per pad, and the specifics of the shale play that is exploited. Due to the prevalence of horizontal drilling for shale gas exploitation, wells are commonly drilled in clusters on multi-well pads. This decreases direct land-use requirements, since multi-well pads can be serviced by the same supporting infrastructure.

Estimated land requirements for developing shale gas well pads were extrapolated from the United States Department of the Interior (USDI, 2008) assuming the use of 16 wells per pad in the TLow scenario, and 2 wells per pad for the THigh scenario. Based on reported values (USDI, 2008; Sumi, 2008; NYCDEP, 2009; NYSDEC, 2011), we adopted a minimum well pad spacing of 32 and 1024 ha (for THigh and TLow, respectively) as the basis for our scenarios.

It is worth noting that the resulting actual well pad density depends on the specificities of the region where the well pads are located, especially the presence of excluded/not-exploitable areas, such as urban settlements or natural protected areas, and may therefore exceed this minimum value.

The corresponding water consumption estimates are based on reported values and are further explained in Vandecasteele et al. (2013). The parameter values used are summarised in Table 2.

2.2. *Defining legislative scenarios*

Uliasz-Misiak et al. (2014) give an overview of some of the legislative aspects currently involved in shale gas exploitation in Poland. At the time of writing there was no specific legislation related to the extraction of unconventional resources, and that outlined for conventional gas resources was applied. This means that an environmental impact assessment is needed only if significant environmental impacts are expected (i.e. if wells more than 1000 m deep are to be drilled in protected areas; more than 5000 m deep in unprotected areas, or a gas production of more than 500,000 m^3/day is expected).

Since we wish to analyse the extent of possible impacts of specific legislative restrictions on the exploitation of shale gas by fracking, we assess two possible regulative frameworks. The first takes into account the minimal restrictions on drilling which may be imposed, or are already imposed, in Poland: from here onwards we refer to this as the 'current' legislative framework. It assumes a relatively high degree of freedom of companies to exploit the resource. The second is a more restrictive scenario, which implements the most limiting regulations noted from the available literature, for example in New York and Pennsylvania States (Blohm et al., 2012). In both scenarios, areas are excluded from the total

Table 3
Overview and comparison of the two legislative scenarios used.

Constraint	Description	Exclusion zone	Data source
Current legal provision			
Natural protected areas	Nature Reserves	Total area	Nationally Designated Areas
Flooded areas	100 year return period flooded area	Total area	BKOP
Urban areas	Urban and industrial areas	Total area	JRC
Road network	All roads, levels 1–8	50 m buffer	TeleAtlas
Railways	All railways	50 m buffer	TeleAtlas
High voltage lines	Transmission lines	50 m buffer	PLATTS
Restrictive-in addition			
Caves and caverns		Total area, 300 m setback	
Mines		Total area, 300 m setback	
Historic gas/oil wells		Total area, 300 m setback	
Water wells	Private and public, ground and surface	Total area, 500 m setback	
Aquatic habitats	wetlands, rivers, lakes and ponds	Total area, 200 m setback	
Special conservation areas	Nature Reserves	Total area, 200 m setback	
Other natural protected areas		Total area	
Any occupied buildings		Total area, 200 m setback	

area considered for shale gas development, according to the legislative restrictions imposed. The parameters defined in both scenarios are detailed in Table 3.

In both cases, all urban areas (regardless of population density) and industrial sites, water bodies, and transport networks were excluded, as well as a buffered area around them, as defined in the legislative scenarios.

Baptista and Linna (2003) indicate that for Poland there is a ‘right of way’, or recommended buffer around power lines of 110–400 kV up to a corridor of 2 × 33.2 m. Taking into account the model’s spatial resolution of 100 m, we assumed a minimal exclusion zone of 50 m around all power lines for the current scenario, and extended this assumption to the major road (all paved roads) and rail network.

Natural protected areas present in the study area include Nature Reserves, Landscape Parks, Protected Landscape Areas, and Natura2000 sites. Wetlands are included in these natural protected areas. The national legislation bans developments within nature reserves and national parks (Uliasz-Misiak et al., 2014; CSO, 2013; Polish Government, 2014a,b), and these have therefore been excluded from development in our current scenario. Whilst mining activities are not explicitly forbidden in the other natural protected areas, they do require some form of permission or special regulation, and were therefore excluded from our restrictive scenario. In fact, in the case of all 44 licenses requested to exploit the resource within Natura2000 sites, the permission was denied (Kozieł, 2010).

According to the Polish Water Act (Polish Government, 2014c), developments within known flood zones are restricted as they potentially hinder flood protection and may increase the risk of flooding. In both scenarios we therefore exclude areas estimated to be affected by a 100-year return period flood.

Protection zones for surface and groundwater are defined and regulated according to the provisions defined in the national Water Act (Polish Government, 2014c) and Environmental Protection Law (Polish Government, 2014a). Since protection zones are defined on a case-specific basis, we did not take into account any additional restrictions in our current scenario, and implemented a 200 m buffer around all water bodies in our restrictive scenario.

Additional constraints applied in the restrictive scenario include the exclusion of areas with various setbacks or buffer zones where no shale gas exploitation is permitted (Blohm et al., 2012; Eshleman and Elmore, 2013).

On the whole, four scenarios were simulated, resulting from the combination of the considered technology and legislative parameters as detailed in Fig. 4.

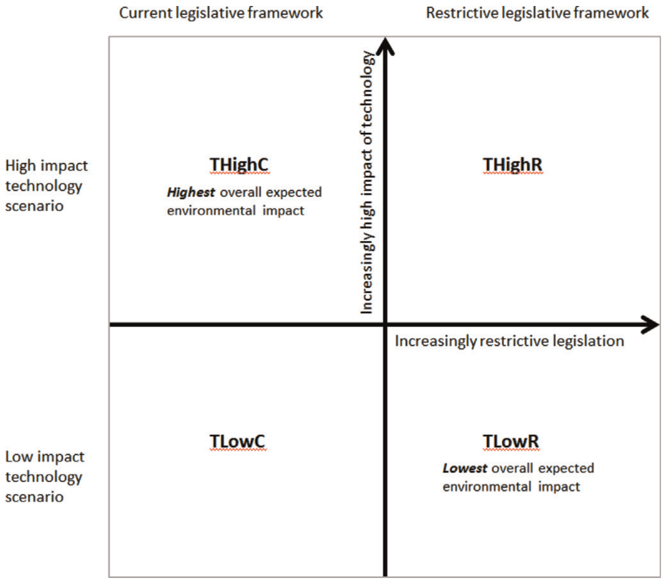

Fig. 4. Overview of the scenario combinations simulated for the study area.

2.3. Land use change simulation

The land-use allocation was performed using the Land Use Integrated Sustainability Assessment Modelling Platform (LUISA). LUISA is a dynamic spatial modelling platform: it simulates future land-use changes based on biophysical and socio-economic drivers, being specifically designed to assess land-use impacts of EU policies (Lavalle et al., 2011b; Baranzelli et al., 2013; Batista e Silva et al., 2013b). The dynamic simulation core of LUISA was originally based on the Land Use Scanner (Hilferink and Rietveld, 1999; Koomen and Van Beurden, 2011), CLUE and Dyna-CLUE land-use models (Veldkamp and Fresco, 1996; Verburg et al., 2006; Verburg and Overmars, 2009), but its current configuration is the result of a continuous development effort by the Joint Research Centre (Lavalle et al., 2011a).

LUISA integrates diverse and specialized models and data into a coherent workflow. It has a modular structure and is organised in three main components: the amount of land claimed per land-use type (Land Demand Module), a set of rules to allocate the requested land (Land Allocation Module), and the computation of indicators to facilitate the analysis of results (Indicator Module).

At the core of LUISA is the EUCS100 model, operating at 100 m spatial resolution (Lavalle et al., 2011a). EUCS100 is based on the dynamic simulation of competition between land uses: it downscales regional projected future land-use demands to a fine spatial resolution. The regional land demands are provided in the demand module by sector-specific economic models, such as the CAPRI model for agricultural land (Britz and Witzke, 2008) and the GEM-E3 model for industrial land demands (EC, 2013). Its spatial allocation rules build on a set of locally influencing factors which together define the suitability of each land parcel for each competing land-use type. The current land use and starting state for the simulation is a refined version of CORINE Land Cover 2006 (Batista e Silva et al., 2013a).

2.4. Calculation of the water exploitation index

The Water Exploitation Index (WEI) is an indicator which assesses the extent to which the environment may be experiencing water stress. It is calculated as the ratio of total water withdrawal for all sectors from the environment to the total amount of water available (EEA, 2010b). The indicator could be calculated taking into account either the total withdrawal, or the actual consumption of water over a year. For this modelling exercise we calculated the WEI for water consumption, which relates only the proportion of water actually used up (i.e. in drinking water, converted into products, polluted beyond direct re-use or otherwise removed from the direct environment) to the total freshwater availability. The calculation of the WEI for consumption is done at each 5-year time step and is used as a limiting factor for the well pad allocation suitability maps-shale gas exploitation is discouraged in areas with a high WEI.

We calculated sectoral water withdrawal maps for each time step, based on a simple model which disaggregates the regional water withdrawal estimates per sector (public, industry and agriculture) to the appropriate land cover classes, and simultaneously forecasts withdrawals based on sector-specific driving factors. These maps were used in conjunction with the average annual freshwater availability derived from the Polish Hydrogeological Institute (PHS, 2012) to compute the indicator. The water use model is described in Vandecasteele et al. (2013), and the use of the WEI to assess the relative impact that the various scenarios have on available water resources is further developed in Vandecasteele et al. (in press).

2.5. Calculation of the suitability layer

We reviewed factors which may influence the placement of shale gas extraction sites, and combined them into a map giving the relative suitability for the allocation of well pads per 100 m pixel. Higher suitability was given to areas where there were favourable conditions, most importantly in terms of geological characteristics and resource availability (both of shale gas and water), but also in terms of infrastructure connectivity (road network and gas pipelines). Areas where the allocation of exploitation sites is forbidden according to our legislative scenarios were excluded, and the allocation was assumed more likely to take place as the distance from those sensitive areas increases. Proximity criteria are set in order to take into account the distance from these excluded areas. The layer is computed so as to measure the Euclidean distance from the nearest excluded area, regardless of the type of area (urban settlement, water body, natural protected area, etc.). A summary of the datasets used is provided in Table 4.

As in Kuhn and Umbach (2011), we used the thickness, depth and thermal maturity to indicate the "geological success", or the productivity of the shale. The thickness of the stratum of shale richest in organic carbon was used as a proxy for the availability of gas in the shale play, based on a study by the Polish Geological Institute of the Lower Palaeozoic Baltic-Podlasie-Lublin Basin (PGI, 2012).

The extent to which freshwater resources are exploited was measured through the computation of the WEI, which was computed dynamically for each time step for the shale play region. Proximity to the existing road network was taken into account as the Euclidean distance to the nearest element of the network. The same approach was used for the existing gas pipelines. The gas distribution networks were extracted from IHS Global Insight (2011), and only the operative lines belonging to the regional/national distribution network were taken into account.

The allocation criteria were combined in a three step process, so as to compile a unique suitability layer to drive the allocation of new well pads. In the first step, the excluded areas were removed from the suitable areas. The different thematic layers were then normalised and standardised between 0 and 1. Depth was rescaled applying an exponential function (Augustine et al., 2006); all the other criteria were normalised applying a linear function. For each layer, 0 corresponded to the lowest suitability represented and 1 to the highest.

Finally, all layers were linearly combined in order to produce one unique suitability layer: each of them was weighted in accordance to its relative importance with respect to the others (Saaty's Analytic Hierarchy Process, AHP, implemented with pair-wise comparison matrices). The weighting was assigned according to a literature review, taking into account the importance of factors in terms of reducing costs to the drilling companies (Husain et al., 2011; IHS Global Insight, 2011; Guarnone et al., 2011), and is summarised in Table 5.

The final weights show an acceptable level of consistency (consistency index $CI < 0.10$). The sensitivity of the results to variations in the input criteria and weights was assessed using the SimLab V2.2.1 programme (SIMLAB, 2013; Saltelli et al., 2000). The

Table 4
An overview of the criteria used in the calculation of the suitability layer.

Criterion	Description	Optimum condition	Data source
Depth	Burial depth of the bottom of Llandovery [m]	Shallowest	PGI (2012)
Thermal maturity	Vitrinite reflectance [%Ro]	Highest	PGI (2012)
Thickness	Average thickness shale deposit [m]	Highest	PGI (2012)
WEI+surface water	Water Exploitation Index [%] Computation by sub-basin	Lowest	(JRC; CSO, 2013)
WEI+ground water	Water Exploitation Index [%] Computation by sub-basin	Lowest	(JRC; CSO, 2013)
Roads	Distance to road or highway access, [m]	Lowest	TeleAtlas
Pipelines and gas infrastructures	Distance to gas pipelines/compressor station [m]	Lowest	HIS
Electric grid	Distance to electric lines [m] All voltages are considered	Lowest	PLATTS
Urban and industrial areas	Distance to populated area [m]	Highest	JRC
Natural protected areas	Distance to protected area [m]	Highest	Natura2000

Table 5
Normalised weighting per criterion used to calculate the suitability layer.

Criterion	Normalised weight
Depth	0.22
Thermal maturity	0.22
Thickness	0.22
WEI surf	0.08
WEI ground	0.08
Pipelines	0.05
Road network	0.04
Power grid	0.03
Urban areas	0.03
Natural areas	0.03

most influential criteria are the geological layers, as expected. The weights with the highest influence on the results are the ones of thickness, depth, WEI (surface and ground water) and distance to pipelines: this indicates that the weights are consistent and coherent with the original value judgement.

2.6. Allocation of shale gas extraction sites (well pads)

The allocation of well pads is implemented in a four-step algorithm. Firstly, all the regions which are too small to host the total development foreseen for one well pad, are excluded from the suitability layer.

The second step entails the allocation of the land required for the operation of the well pads. Only adjacent pixels are developed, until the required amount of hectares has been allocated. The land to be developed is selected maximising the allocation function, which takes into account the suitability index and a neighbourhood factor. The latter plays a more influential role in the initial stage of development, i.e. when the number of surrounding developed cells is low.

Third, a construction buffer is allocated around the newly developed well pads. The cells composing the buffer are selected within the land available for the development. The buffer takes into account the land needed in the construction phase of the well pads: therefore, it does not change the current use and becomes unavailable to any land-use change for the next simulation period (5 years). After 5 years, the construction buffer is removed.

Finally, a minimum distance factor is applied, in order to forbid the development of a new well pad within the direct vicinity of the already existing exploitation sites.

2.7. Assessment of overall impact of shale gas development

We assessed the potential impact of shale gas extraction activity on the fragmentation of natural areas and land of Polish

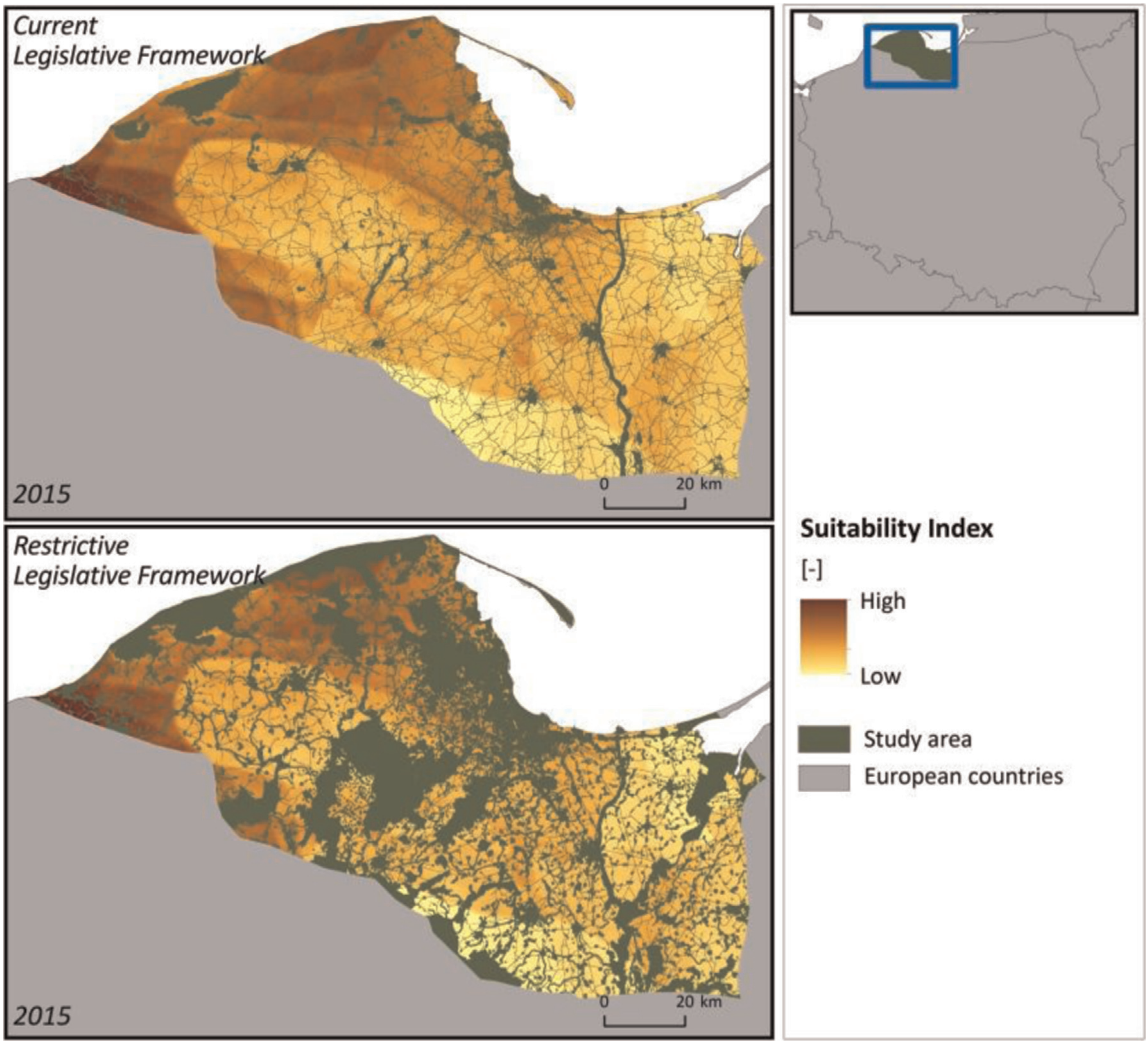

Fig. 5. Suitability maps as computed for 2015 for the current and restrictive scenarios.

Green Infrastructures (GI) within the study area. In the definition of Green Infrastructures we included wetlands, HNV farmland and forest land: for a detailed description of the methodology applied (morphological analysis), see Riitters et al. (2009), Wickham et al. (2010), Drohan et al. (2012a,b). We also calculated the distance of well pads placed from important features, such as natural reserves and drinking water wells, in order to be able to compare the potential impact that the different scenarios may have on the landscape.

3. Results

The results varied greatly between the scenarios modelled. In what follows we compare the scenario with the highest expected environmental impact (THighC) with that expected to have the lowest overall environmental impact (TLowR).

3.1. Suitability for shale gas development

Fig. 5 shows the suitability maps calculated for the study area for the first time step (2015) of the current and restrictive scenarios (at the beginning of the simulation, these maps are identical for the low and high development scenarios).

The most favourable areas are located in the north and northwest of the study area, mostly due to the geological constraints applied. The restrictive scenario results in a greater fragmentation of areas available for shale gas extraction, especially due to the exclusion of all protected natural areas.

The Water Exploitation Index (WEI) for consumption as calculated for use in the final time step of well pad allocation is shown in Fig. 6 for the THighC and TLowR scenarios. In both cases, the highest WEI values are found along the northern coast and the Wisla Bay area. This means that during the allocation part of the land use simulation, well pads are preferentially placed away from these areas, where water exploitation is already relatively high. The impact of the greater density of well pad placement and higher water consumption in the THighC scenario as compared to the TLowR is reflected in the significantly higher water exploitation in the north of the study area.

3.2. Land use for shale Gas development Scenarios

Fig. 7 shows the allocated well pads for the highest and lowest impact scenarios (THighC and TLowR) for the final year of the simulation (2030). Both the active well pads (placed in 2025 or 2030), and the inactive well pads (placed in 2015 or 2020, with a lifespan of 10 years) are shown. In both cases, all well pads were allocated to the northern and northwestern extents of the study area, where suitability was highest. The allocation patterns are quite different, however. The greater distance required between well pads in the TLowR scenario, and the fragmentation of

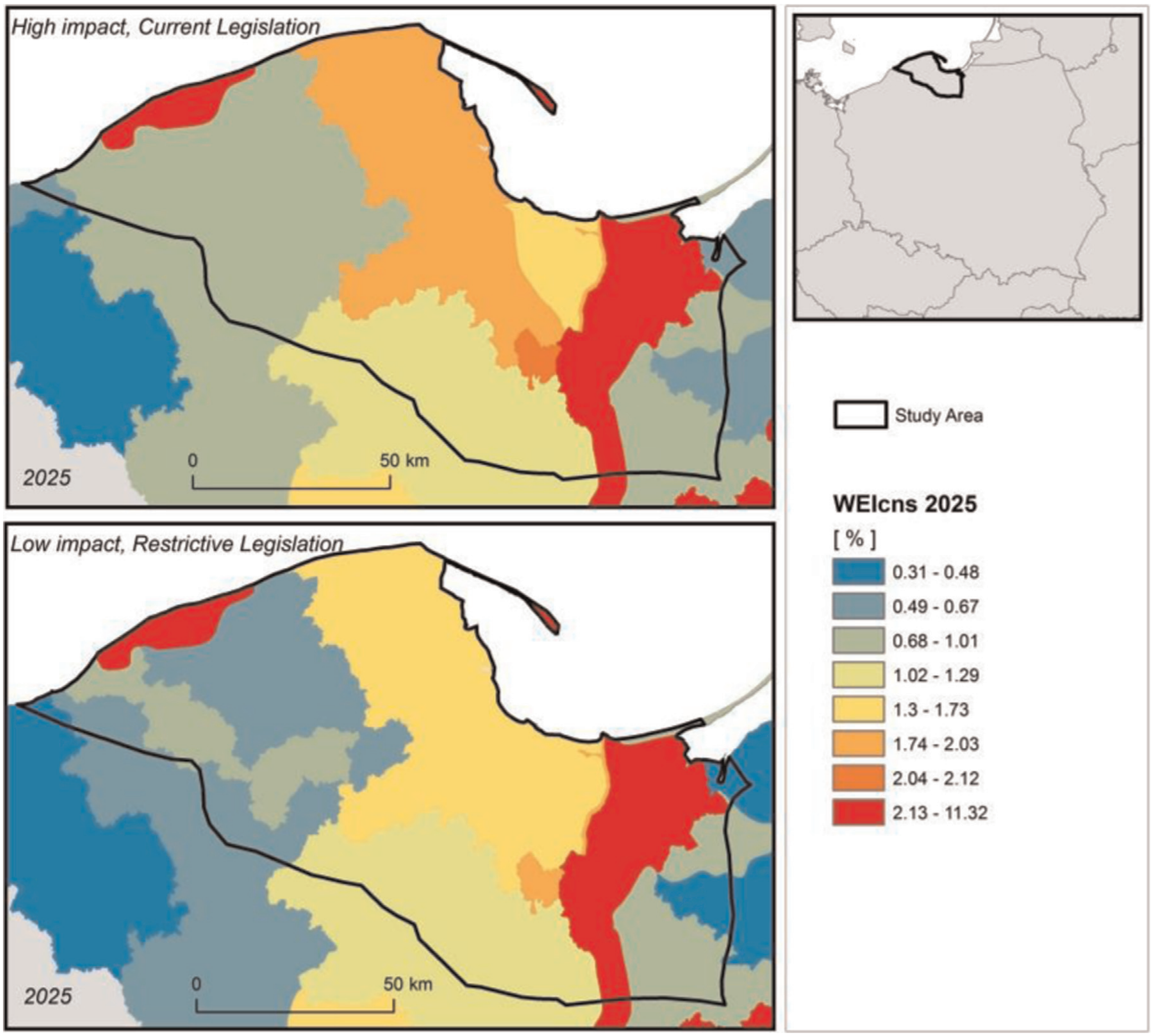

Fig. 6. The average WEI for consumption (WEIcns) calculated for the high impact, current legislation (THighC) and low impact, restrictive legislation (TLowR) scenarios.

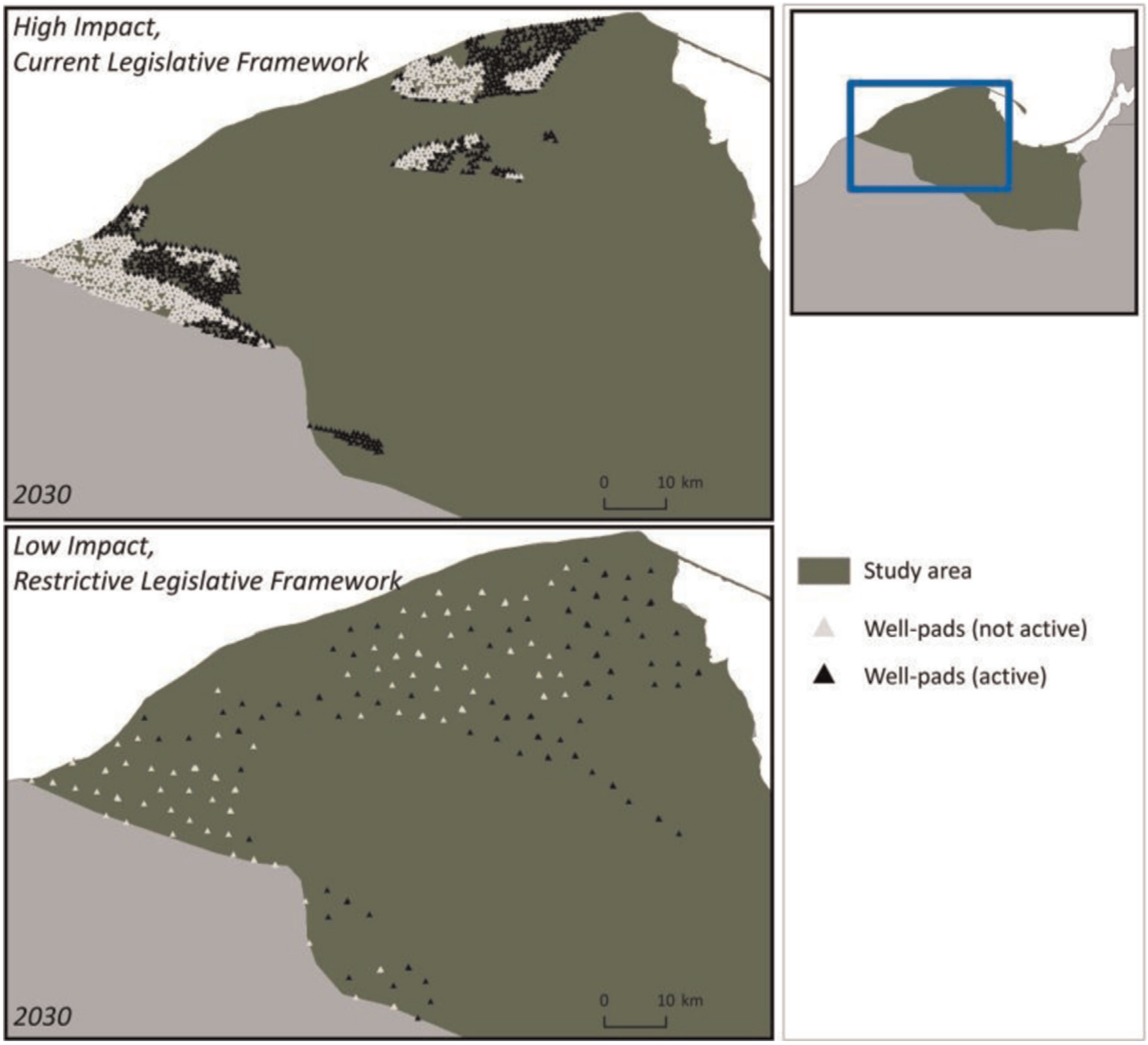

Fig. 7. Simulated well pad allocation under the high impact, current legislation (THighC) and low impact, restrictive legislation (TLowR) scenarios for 2015–2030.

available land due to the greater legislative restrictions applied, result in a far less dense distribution.

The simulated land-use map and well pads are shown in more detail in Fig. 8 for the area northeast of the city of Lebork, for the year 2030. It should be noted that each well pad in the THighC scenario hosts only 2 wells, while the well pads in the TLowR scenario host 16, meaning that overall there are fewer wellpads placed in the TLowR scenario.

The percentage of total well pads developed in each land-use class for each scenario is given in Table 6.

For all scenarios, the majority of well pads are developed in arable or forest areas, with only a small share developed in pastures or other natural land, and none on land being used for permanent cultivation (which covers only 0.1% of the study area).

A clear difference between scenarios is seen in the allocation of well pads within agricultural landscapes of particular importance for supporting species and habitat diversity. This kind of farming landscape is denominated High Nature Value farmland (HNV farmland; EEA, 2012) and the need for its conservation is acknowledged by the Common Agricultural Policy (CAP) of the European Union (EC, 2006, 2009, 2011). 7% of well pads were developed inside areas currently mapped as HNV farmland under the THighC scenario; this share increased to nearly 12% under the TLowR scenario. The restrictive legislative scenario limits the allocation of well pads in forest areas significantly. In contrast, in both the high and low development rate scenarios considering current legislation (so having no explicit ban on shale gas extraction within protected areas except for nature reserves, which cover only 0.63% of the study area), some 24% of well pads are allocated within protected areas. More detailed (per land-use class) shares of occupation of both HNV farmland and protected areas, are reported in Table 6.

Under both the TLowR and the THighC scenarios, well pads that are developed within Green Infrastructure (GI) affect core areas the most, and only marginally other functional zones, such as edges and perforated GI. Nevertheless, under the THighC, more than half of the land taken to develop well pads is indeed eroding GI, while under the TLowR scenario, the majority of the well pads are developed on land not belonging to GI.

In order to assess overall potential impact in terms of land take (i.e. implying sealing of land which was not already artificial) for shale gas development activities, a comparison can be made with total land take due to new industrial activities as a whole within the shale play boundaries. Overall, in the year 2030 the land taken up for shale gas extraction as a percentage of the total land used for industrial purposes within the study area, is on average 7% (592 ha) for the low development scenarios (TLowC and TLowR), and 12% (1176 ha) for the high development scenarios (THighC and THighR).

Fig. 9 reports the distances from all allocated well pads to natural reserves and protected sites, built-up land and drinking

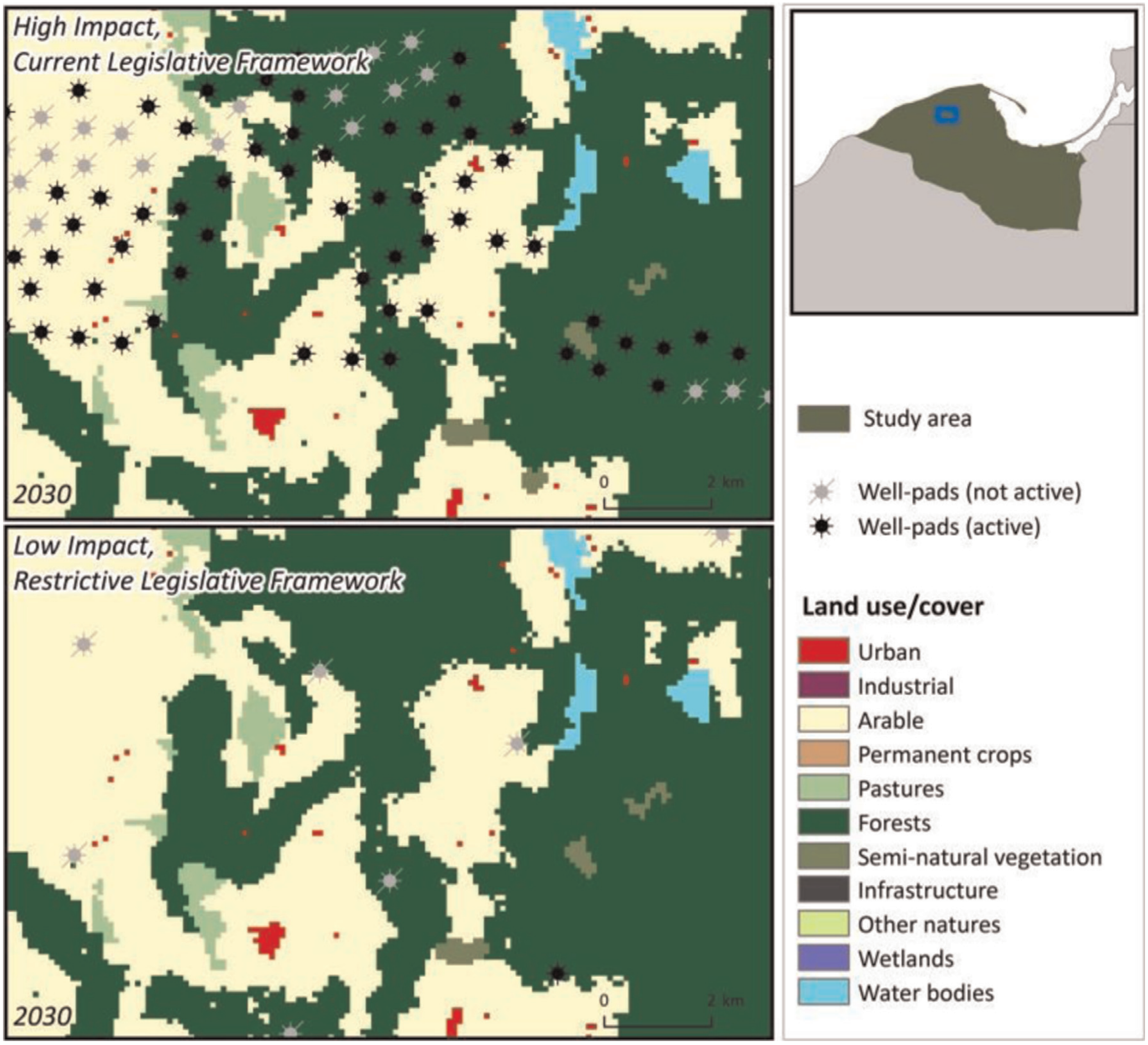

Fig. 8. Detail of the simulated land-use map and well pad allocation under the high impact, current legislation (THighC) and low impact, restrictive legislation (TLowR) scenarios for 2015–2030.

Table 6
Percentage of total well pads developed in each land-use class. The relative percentages of well pads falling within HNV farmland and protected areas, per land-use class, are also reported.

	High, current THighC	High, restrictive THighR	Low, current TLowC	Low, restrictive TLowR
Arable land	50.6	63.8	40.4	52.2
Of which in HNV farmland or protected areas	*8.4*	*1.2*	*10.0*	*3.2*
Pastures	4.1	4.6	5.7	10.0
Of which in HNV farmland or protected areas	*100*	*100*	*100*	*100*
Forest	41.6	30.5	50.5	36.8
Of which in protected areas	*0.8*	–	*38.5*	–
Other natural land	3.7	1.1	3.4	1.0
Of which in protected areas	*2.4*	–	*30.0*	–

water wells for the THighC and THighR scenarios. The average distances are similar under both scenarios. Due to the different legislative framework, the THighC development scenario shows more well pads allocated in the close proximity of landscape sites or Natura2000 areas. Under the THighC scenario, the share of land taken for shale gas exploitation within 500 m from drinking water wells is significantly higher than under the TLowR scenario, thus posing potential water quality concerns.

4. Discussion

A modelling approach was used to assess the overall potential

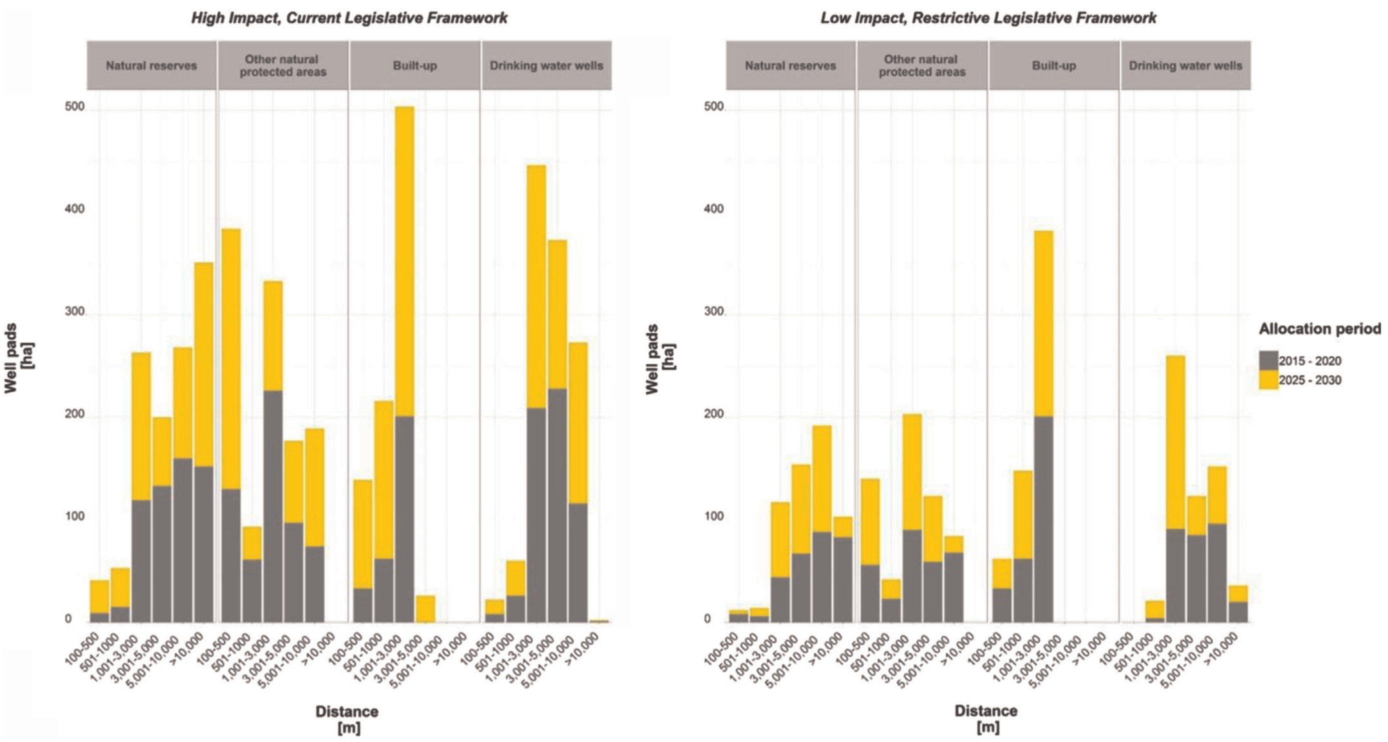

Fig. 9. Distance of well pads allocated from natural reserves, other natural protected areas, built-up land (urban and industrial) and drinking water wells for the high impact, current legislative (THighC), and the low impact, restrictive legislative (TLowR) scenarios for 2015–2030.

impacts of shale gas development in Northern Poland in terms of land use. This methodology could be applied to any study site where sufficient data is available. Numerous factors impacting the suitability of land for shale gas extraction were assessed. Although the geological specifications are the major concern in guaranteeing the profitability of development of the resource, several other parameters proved important. This included the availability of water and access to road networks and gas pipelines. Further analysis on the uncertainties associated with the included factors should be carried out (Feizizadeh et al., 2014). In addition, numerous technical parameters affect the placement of well pads, including requirements such as minimum distances from adjacent well pads and from built-up areas. The range of variability of all these factors was taken into account by defining a range of possible development scenarios, in particular assuming two rather extreme technology-based configurations, based on current practises and available literature.

An important element of uncertainty of our exercise is directly linked to the resource estimates and the possibility of providing accurate predictions of well performance (Sovacool, 2014; Kinnaman, 2011). Also, even though in this analysis we assume a constant rate of development, the scale of shale gas development activities will likely increase at an accelerating rate over time as experience is gained and infrastructure developed. If we take as term of comparison data reported for the US (see, as examples, Hughes, 2014; Wang et al., 2014), assuming a constant rate of development might have led to underestimating the environmental impacts associated with the drilling activity in the first years of the simulation. It is, however, out of the scope of this study to predict this potential acceleration, and a constant rate of development was assumed.

The overall construction area assumed in the developed scenarios includes land necessary for supporting infrastructures, such as access roads, utility and transportation lines, in addition to processing areas. Nevertheless, it was not possible to take into account the actual footprint of these linear elements, and their impact on habitat and landscape fragmentation (Drohan et al., 2012a,b; Johnson, 2010). This impact may be even greater if we take into account that shale gas extraction sites can be equated to heavy industrial zones, having intense truck traffic (Sovacool, 2014; Krupnick et al., 2014).

In the current analysis, no additional assumptions were taken with regard to the post-production phase of drilling and extraction activities: the land used in the production phase of each well pad is maintained after the well pad lifespan, but in a non-active state. Clean-up costs associated with the decommissioning phase of the well pads are in general likely to be substantial (Sovacool, 2014), and strongly correlated with the depth of the wellbore and site accessibility (Mitchell and Casman, 2011), parameters which are considered in the study. Site restoration and remediation, in the absence of clear regulations that set obligations and minimum criteria at European level, are likely to pose an additional threat to environmental and human health (Davies et al., 2014).

A potential improvement of the modelling exercise would therefore be the inclusion, among the factors driving the well pad allocation, of information about the location of facilities such as water treatment plants or disposal sites for hazardous waste materials, and any other factor that might also affect clean-up and decommissioning costs. For instance, within or in close proximity of the study area there are 10 such treatment plants that are registered in the E-PRTR (European Pollutant Release and Transfer Register; EEA, 2013). Similarly to post-production costs, the potential impacts also do not include the possible occurrence of incidents and drilling problems, and related costs (Davies et al., 2014; Mitchell and Casman, 2011; Husain et al., 2011).

There are several additional potential legislative restrictions which were not applied for our study area scenarios, but should be noted. Although the minimal depth to the target formation is 1 km in our study site, there should be a restriction on drilling for areas where this depth is less than 600 m. Drilling in the vicinity of dams, cultural and historical sites, and limestone outcrops (Eshleman and Elmore, 2013) should also be restricted. The one dam within the study area (Dolina Wierzycy) and cultural sites were already located inside protected zones, so are not specifically mentioned. We lacked the necessary data to be able to take into account the presence of limestone outcrops.

In the definition of the suitability layer there are also several factors which have been omitted in our specific case, but may be of importance in other study areas. No data concerning the current usage level of the various gas distribution segments was available and, therefore, this information was not included in the analysis. Other gas infrastructure such as compressor stations, operating storages, processing and distribution points, which should be taken into consideration (Agbaji et al., 2009), were not available within the study area or in its vicinity according to the database.

The presence of Normally Occurring Radioactive Materials (NORM) such as Uranium, Torium, Caesium and Potassium in sites chosen for shale gas extraction (Warner et al., 2013; Almond et al., 2014) may incur additional costs to the company, due to pollutant regulations related to the health and safety of workers, and special requirements for waste disposal (Sovacool, 2014; DNV, 2013). Nevertheless, this possible cost was assumed to be negligible as compared to the total cost of operation, and was therefore not taken into account. According to published data (Ernst and Young, 2014; IHS Global Insight, 2011), drilling and completion costs account for roughly 60% of the total expenditure for a single well pad, whereas costs associated with waste water treatment, disposal and transportation (also taking into account specific requirements for the presence of radioactive materials) account for less than 6%. In addition, the presence of Uranium, Torium, Caesium and Potassium (background concentration) is naturally relatively low within the study area (Panstwowy Instytut Geologiczny, 1993a,b).

Both the seismic activity of the study area (very low, 0–0.2 PGA [m/s^2], Giardini et al., 1999) and the topography (the average slope is 1.2%) were also considered as possible exclusion factors, but in both cases the possible impact was seen as negligible, and the parameters were not included.

An additional improvement could be the inclusion, among the factors affecting the local suitability for developing well pads, of the current use or cover of the land to be converted: the ownership patterns, the value of the land, or the general costs for acquiring/leasing the land and clearing it.

Finally, the use of European-specific data on technology, land and water requirements, when it becomes available, would reinforce the approach. Although in most cases data derived from long-standing US shale plays can be applied, there may be discrepancies with the values actually recorded in Europe as shale gas development progresses. Technological parameters may vary greatly with physical conditions, meaning that local data should preferentially be used in such an assessment. In as far as possible, Polish data has been used, but there remains a reliance on US data for several parameters, especially in defining our development scenarios, which may reduce their predictive value.

5. Conclusion and policy implications

Several specific conclusions can be drawn about the development of shale gas within the study area and more generally on the optimal implementation of extraction operations in Europe. Here we look at answering the questions posed in the introduction:

5.1. What are the discrete and potential aggregate land-use requirements associated with shale gas development?

The scenario results show that the land required for the development of shale gas in Northern Poland is significant. The lowest and highest impact scenarios vary substantially in terms of both projected land consumption and allocation patterns of the well pads. In the final year of the simulation, between 7% and 12% of the land taken for industrial activities within the study area is attributed to the shale gas industry. These figures become especially important when considering the possible implications and competition for land with other uses at the local scale.

5.2. What are the associated potential land-use conflicts in Poland, including competition with alternative land uses?

The extent to which shale gas development might actually result in landscape fragmentation and conflicts with other land users, is highly dependent on the anticipated scale of development in the specific geographical context.

The spatial distribution of the exploitation sites is heavily dependent on the density parameter, implemented as a minimum distance between well pads. The effect of this parameter is emphasised by the specificities of the landscape overlaying the shale plays. Highly complex, multi-use landscapes imply the presence of numerous barriers to drilling activities. This aspect, affecting also the development of the necessary infrastructure (roads, gas pipelines, service areas, etc.), might further exacerbate the impact of local disturbances, such as noise pollution, air quality degradation, vibrations from traffic, or habitat disruption, on the resident population and natural environment (Jenner and Lamadrid, 2013; Jordaan et al., 2009; Johnson, 2010).

Overall, well pads are most commonly placed on existing arable land, followed by forest and other natural areas, and to a lesser extent pastures. The competition with agricultural land may become important at the local scale, especially considering that there will also be a certain minimum distance that farmers may wish to keep from active well pads due to environmental concerns. On the other hand, the extent to which shale gas extraction should be permitted to fragment natural areas and forests should also be limited.

5.3. What impact could legislative constraints have on the land take for shale gas development?

Both the development rate used and the legislative restrictions applied greatly influence the resulting distribution of well pads. The results of our analysis have demonstrated that important and sensitive elements of the landscape, such as HNV farmland and Green Infrastructures, may still be significantly affected by the shale gas extraction sites, even if developed at relatively low density. A policy intervention would therefore be necessary to minimise impacts on such elements, in some cases requiring a modest displacement of the well pad.

For this case study, the use of a restrictive, rather than current legislation, and a lower development rate would result in the lowest environmental impact of shale gas extraction. This would result in a much less dense distribution of well pads, with lower land and water requirements, and therefore greatly minimise the direct local impacts on resources. Increasing the number of wells per pad does allow for reduced infrastructure requirements and better economy of scale, also in relation to post-production and restoration costs (Mitchell and Casman, 2011): it is, however, also likely to pose additional burden on a very local scale, i.e. in the immediate vicinity of the site (Drohan et al., 2012a), and this has to be duly taken into account by the policy maker.

Several policy recommendations can be made based on the results of our analysis. Shale gas development should be restricted as much as possible within natural parks and protected areas (if unregulated, some 24% of well pads are developed within protected areas). Given the diffuse presence of valuable protected natural sites in areas characterized as most suitable for shale gas extraction activities, this ban should be strictly enforced and not left to the discretion of the authorities issuing permits on a project basis.

There should be an appropriate minimal distance from sensitive targets, such as inhabited areas and drinking water wells. According to our analysis, assuming the current legislative framework, as much as 28% and 6% of land developed for extraction activities are placed in proximity (within 1 km) to inhabited areas and drinking water wells, respectively. This distance is considered the upper limit for evaluating high level risks posed to the environment and inhabitants (Meng, 2015).

The results of our analysis highlight how the density of well pads, and the minimum allowed distance between them, affect the spatial distribution of the sites and, in consequence, the fragmentation of the landscape. In this regard, multi-wells pads appear to perform better. Nevertheless, the cumulative effect of dense shale gas development and its local impact on the environment and human health remain considerable, due to the diffuse presence of valuable natural and semi-natural habitats in the study area, and the level of activity of the single well pad. In addition, the risk of failure has to be duly taken into account: at average pace of shale gas development, even a very low failure rate could have serious environmental consequences.

The role of technical advances in affecting the spatial configuration of well pads and the probability of failure has to be acknowledged. Enhanced communication between regulatory agencies and operating industries could support more effective policies and better informed investment decisions on infrastructure development and maintenance (e.g. waste water treatment plants and road network).

The scenarios analysed in the paper highlight how, independently from the deployed technology, the risk of extraction activities negatively impacting sensitive targets is not negligible and constitutes a possible source of conflict. The role of public acceptance is therefore crucial: the effectiveness of environmental regulations and targeted policies could be improved by the involvement of different ruling authorities (from the central to the local level), and by a combination of public and regulatory scrutiny, enhancing the communication with the public.

Finally, since shale gas extraction is an extremely site-specific activity (Sovacool, 2014), more detailed recommendations should be made on a case-by-case basis to minimise the impact on the environment locally. In particular, our analysis highlights the risk that adopting a more stringent legislative framework, which includes banning shale gas extraction activities in natural protected areas, might cause a greater impact on HNV farmland.

From the US experience, oil and gas production methods deployed under less restrictive legislative frameworks are not consistent with regulations that are established by states with higher environmental protection standards (Eaton, 2013). An effective regulatory framework should establish clear restrictions on developable areas, as highlighted by our analysis. Such a framework should also target all the main areas of concern related to shale gas extraction activities (Kotsakis, 2012). A set of proper regulatory tools should be deployed, from licensing based on both strict regulation and project-based evaluation, to a monitoring system.

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