POTENTIAL FOR GEOLOGICAL CARBON SEQUESTRATION USING DEEP SALINE AQUIFERS IN THE ILLINOIS BASIN

DECEMBER 4, 2015

GIS TERM PAPER

Julien Botto

Table of Contents

Introduction

Geological carbon sequestration (GCS) is an emerging technology describing long-term storage of CO2 to mitigate the effects of fossil fuel combustion for electricity generation on climate change. It is a way to reduce the atmospheric and marine accumulation of greenhouse gases released by burning fossil fuels.

CO2 is first captured as a by-product in processes related to petroleum refining or from flue gases from power. Then it is transported by pipeline to the injection site where it will be injected for long-term storage (*fig.1*). There are four main types of carbon sinks:

- Deep saline aquifers
- Depleted oil and gas reservoirs
- Salt beds or caverns
- Unminable coal beds

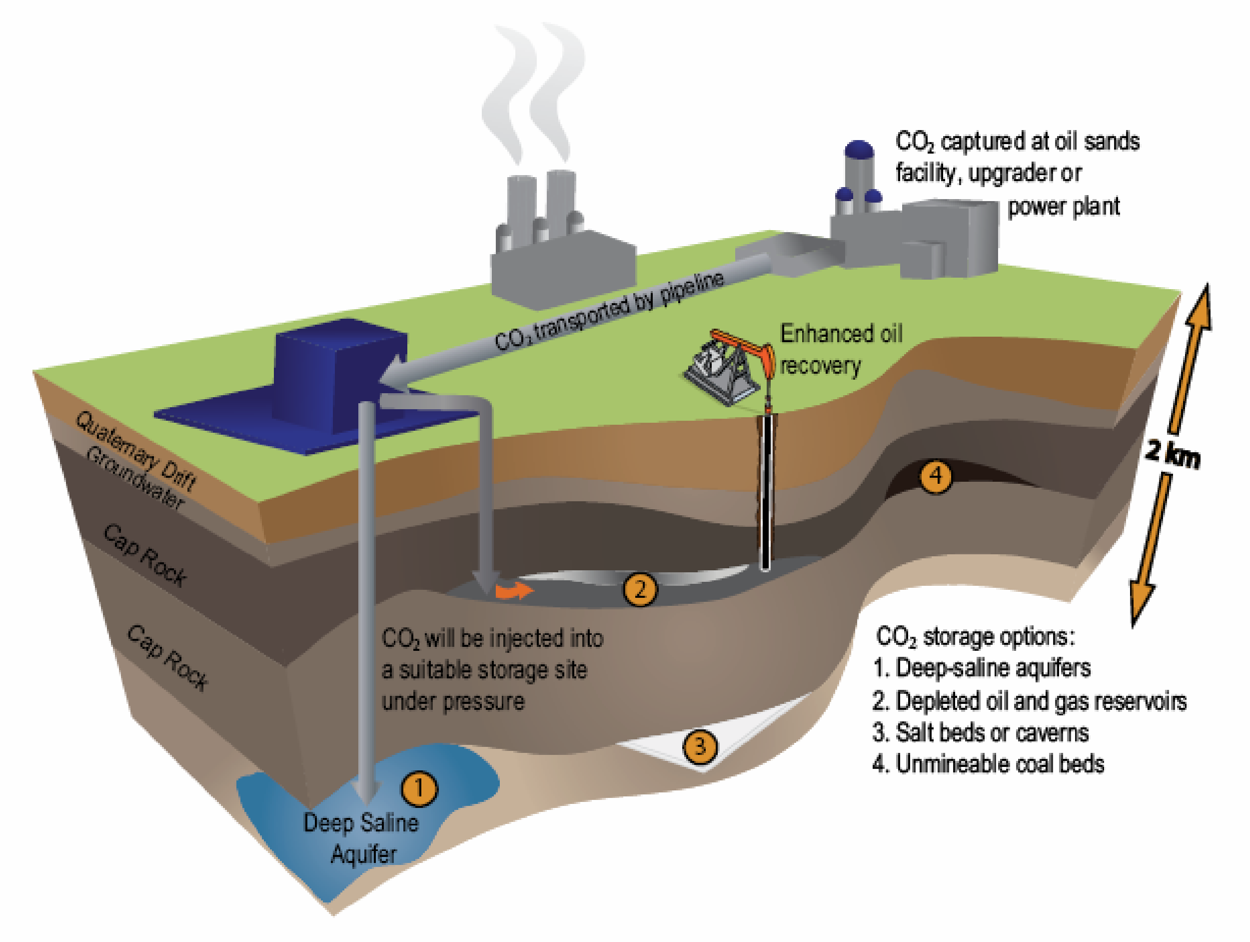

Figure 1: General schematic of GCS

Background

A large demonstration of this technology is performed under the direction of the Midwest Geological Sequestration Consortium in the Illinois Basin at the Decatur site. My research is part of this project and is looking at using a deep saline aquifer – the Mt.Simon sandstone – as a sink for carbon storage. I thus wanted to see why this location was chosen in particular and was also interested in the overall potential of GCS in the entire Illinois basin.

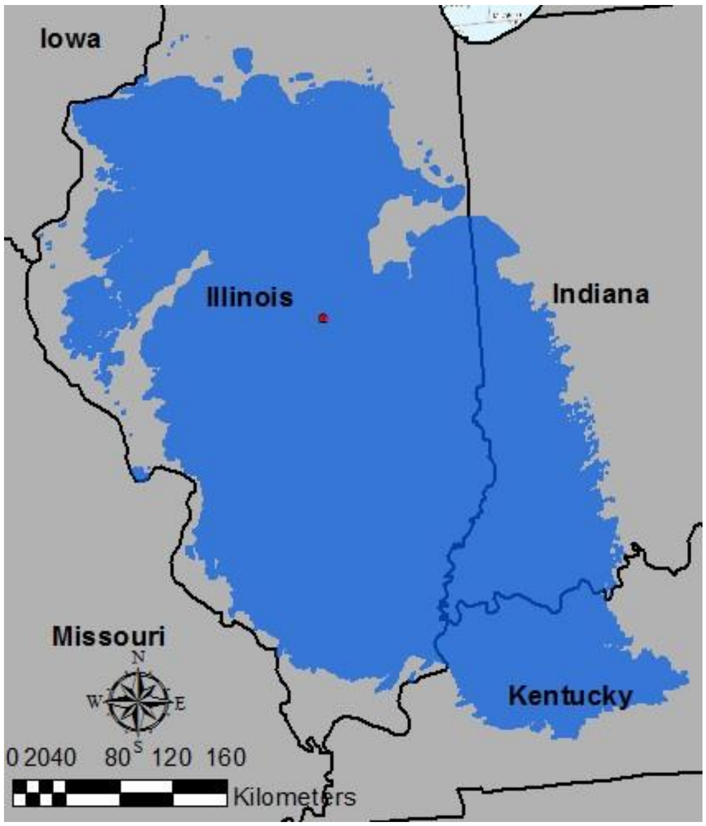

Figure 2: Location of the Illinois basin and the Decatur site

Objective

The objective of this paper is to assess the potential of GCS using deep saline aquifers in the Illinois basin. To do that I will:

- determine the different criteria for GCS,
- map those criteria,
- determine the areas within the Illinois basin where carbon sequestration is feasible,
- determine the areas were carbon sequestration is feasible and economically beneficial.

Methodology

I first had to organize all the parameters which play a role in the success of carbon sequestration in categories of increasing importance. I then looked for the data corresponding to those parameters. I mapped each parameter – with more or less transformation under GIS – in order to obtain visual results as clear as possible. Afterwards, I imposed conditions on all those parameters in GIS to get the areas which meet all GCS conditions. Finally, I organized those areas in terms of economic feasibility.

Parameters

There are a lot of parameters to take into account when doing an assessment of GCS potential. I have thus created categories and organized them by degree of importance in order to have a better understanding of the determining factors in that technology (*fig.3*). Parameters can be classified in categories which answer the following questions:

- Is it possible?
- Is it easy?
- Is it convenient?
- How much CO2 can be stored?

Is it possible?

The primary parameter to look at is the depth of the potential formation. Indeed, it should be deep enough so that it is far away from drinkable groundwater tables but not too deep so that the drilling would be economically feasible. A good estimate is a formation between 2,500ft and 8,000ft.

The salinity of this aquifer should be high enough so that the water could never be used for agricultural or drinking purposes. We chose to fix the lower limit of Total Dissolved Solids (TDS) at 30,000mg/L.

Finally, there should be a thick impermeable layer on top of this formation so that the CO2 injected there can never leak and move up towards the surface. Again, numbers may vary but a good estimate will be a thickness of caprock over 400ft.

Is it easy?

In order to inject CO2 in the subsurface easily, the permeability of the formation should be as high as possible. There are no fixed requirements for that parameter but we will remember this general trend.

The CO_2 injected has to be at a supercritical state (where distinct liquid and gas phases do not exist) because at this state, it has the density of a liquid but flows like a gas. Those characteristics make the injection easy and allow a long term storage because the dense fluid will have a tendency to "sink" into the formation and thus will not leak up to the upper parts of the soil. The conditions for a supercritical phase of CO_2 are a pressure above 1070 psi and a temperature above 32°C.

Is it convenient?

It is also important to look at the distance of the potential carbon sinks from the carbon sources. Thus, it is crucial to map the location of the different sources which produce CO_2 and to see how much is emitted in the air.

It is also interesting to map the location of existing CO_2 pipelines to see how convenient it would be to transport the CO_2 from a source to a sink.

How much CO2 can be stored?

Finally, the last parameter to investigate is the amount of CO_2 which can be stored underground. This mass is notably dependent on the porosity and the thickness of the formation.

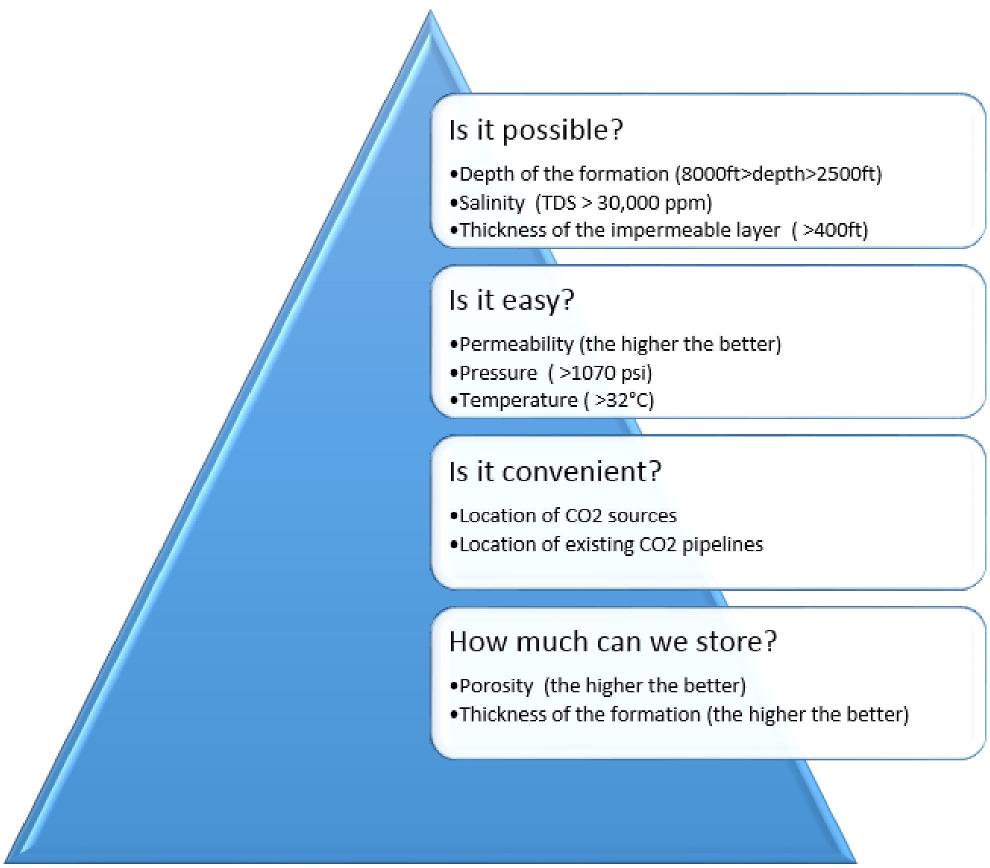

Figure 3: Parameters ranked by degree of importance (from high to low)

Data

The data were mainly collected from two sources. The first one is a report published by the Bureau of Economic Geology in 2012 entitled *Sequestration of Greenhouse Gases in Brine Formations.* From this database, I was able to extract shapefiles of the Mt. Simon sandstone, wells data for the TDS values and DEMs of the pressure and temperature.

The second main source I used was the National Carbon Sequestration Database and Geographic System (NATCARB) atlas V released in 2015. From this database, I was able to extract the depth of the formation, the storage capacity and the locations of CO2 sources along with the amount of CO2 emitted. Those GIS files were using a 10km X 10km grid so those data were a little more detailed than the previous ones.

GIS

All the data that I acquired was already in a GIS format but I had to modify them in order to be able to use them in the most convenient way possible. First, I had to constrain all those data within the frame of the Illinois basin using the "Topo to Raster" tool with the Illinois basin as "boundary". This allowed me to reduce the data from the whole US to my area of focus. Thus, with a lower scale, I was able to better see the differences within the Illinois basin.

I also used this tool for the depth and thickness of the formation. Indeed, I transformed the isopach maps (contour lines of equal thickness) into a raster where I was able to attribute colors for the different depth and thickness which gave a much better visual result.

In order to produce the salinity map, I used the Interpolation tool under GIS because I originally only had wells data. GIS interpolated those data points in order to create a map of the whole region.

Lastly, I had to set conditions on each of those parameters using the "Raster Calculator" tool to see where the potential sites for GCS were located.

Results

Potential formation candidates

First I had to find the best formation possible for potential GCS in this region. Thus, I mapped the formations present in the Illinois Basin (*fig.4*). There are two: the St. Peter Sandstone and the Mt. Simon Sandstone. When I mapped the depth of the St. Peter Sandstone, I found that, except for the very south region of the basin, it was not deep enough. Indeed, as it was mostly inferior to 2,500ft, I decided to rule it out and to focus only on the Mt. Simon Sandstone. This was comforted by the fact that, for the Decatur Project, the engineers decided to work only with the Mt. Simon Sandstone.

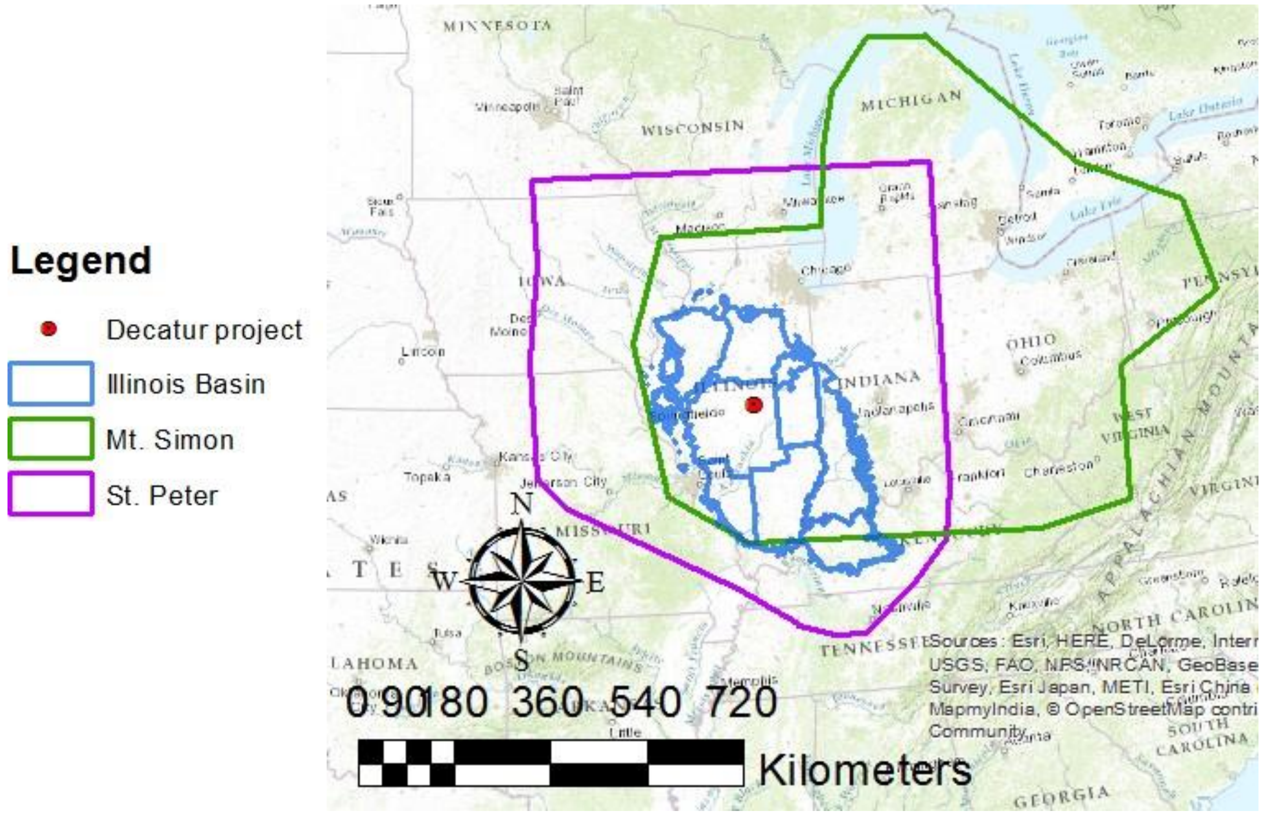

Figure 4: Formations in the Illinois Basin

Is it possible?

I now had to investigate if the Mt. Simon is a good candidate. To do so, I mapped the depth of this formation (*fig.5*), the salinity (*fig.6*) and the thickness of the impermeable layer (*fig.7*).

We can see as a general trend that the depth and salinity are increasing from north to south. We can also noticed that except from the extreme north and south-west parts, the depth of the formation is between 2,500 and 8,000ft, which is the condition for an optimal GCS site. The salinity is also for the most part way above the threshold of 30,000 ppm TDS so that parameter should not be problematic.

The impermeable caprock on top of the Mt. Simon Sandstone is called the Eau Claire and covers Illinois entirely. I was not able to find a GIS version of this map but we can still observe that this formation has a thickness inferior to 400ft only in the western part. So, in all the eastern part of the Illinois Basin, the CO2 injected will not be able to leak into the shallower subsurface due to this thick impermeable layer.

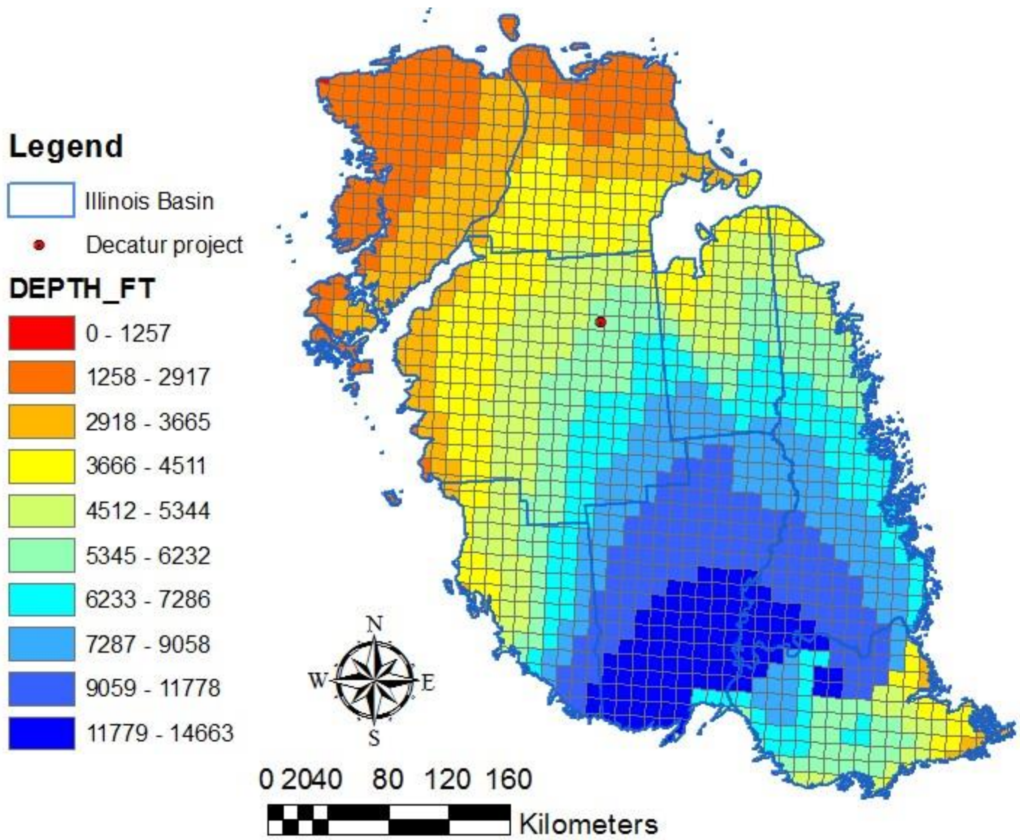

Figure 5: Depth of the formation in the Illinois basin (ft)

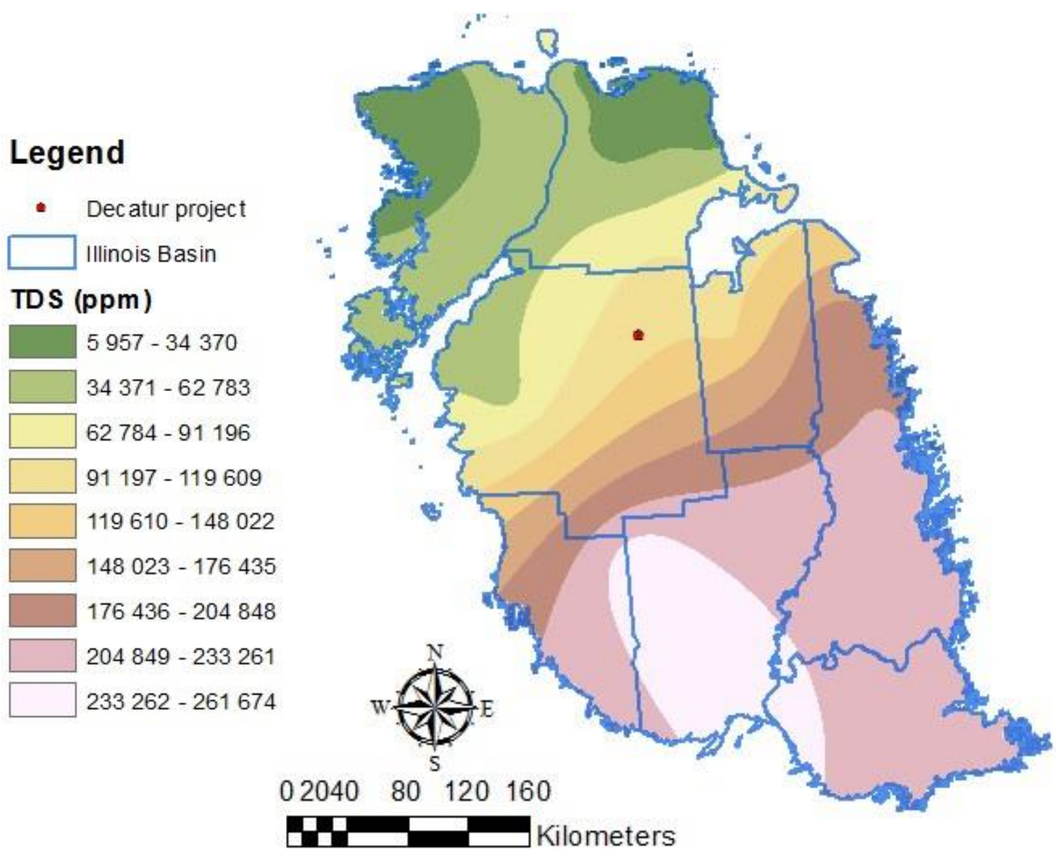

Figure 6: Salinity in the Illinois Basin (TDS in ppm)

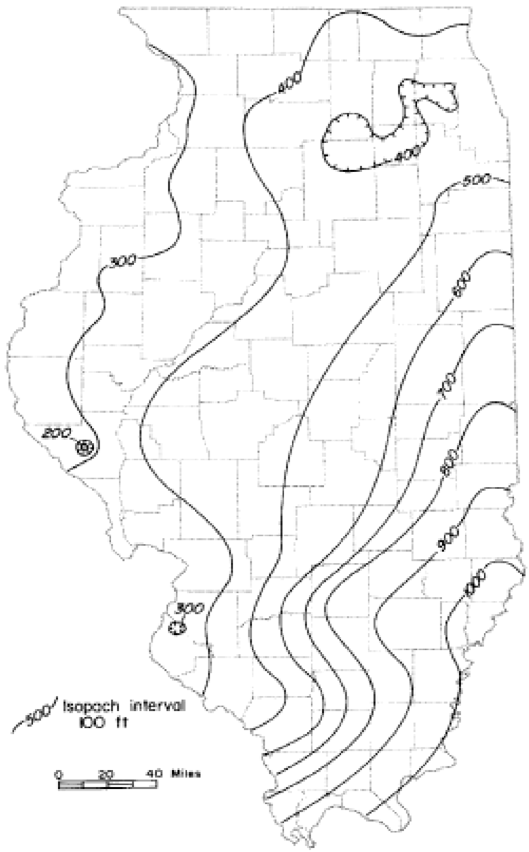

Figure 7: Thickness of the Eau Claire

Is it easy?

The pressure and temperatures displayed in figure 8 and 9 were taken at the middle of the formation. They are very similar to each other and also correspond to the map of the depth of the formation. Indeed, the deeper the formation is, the higher temperature and pressure will be, so those maps are coherent. We can also see that in nearly all the basin, the CO_2 will be at a supercritical state (P>1070psi and T>32°C).

Unfortunately, I was not able to find the data for permeability. However, this is not as critical as other parameters because there are no value below which this technology cannot be applied.

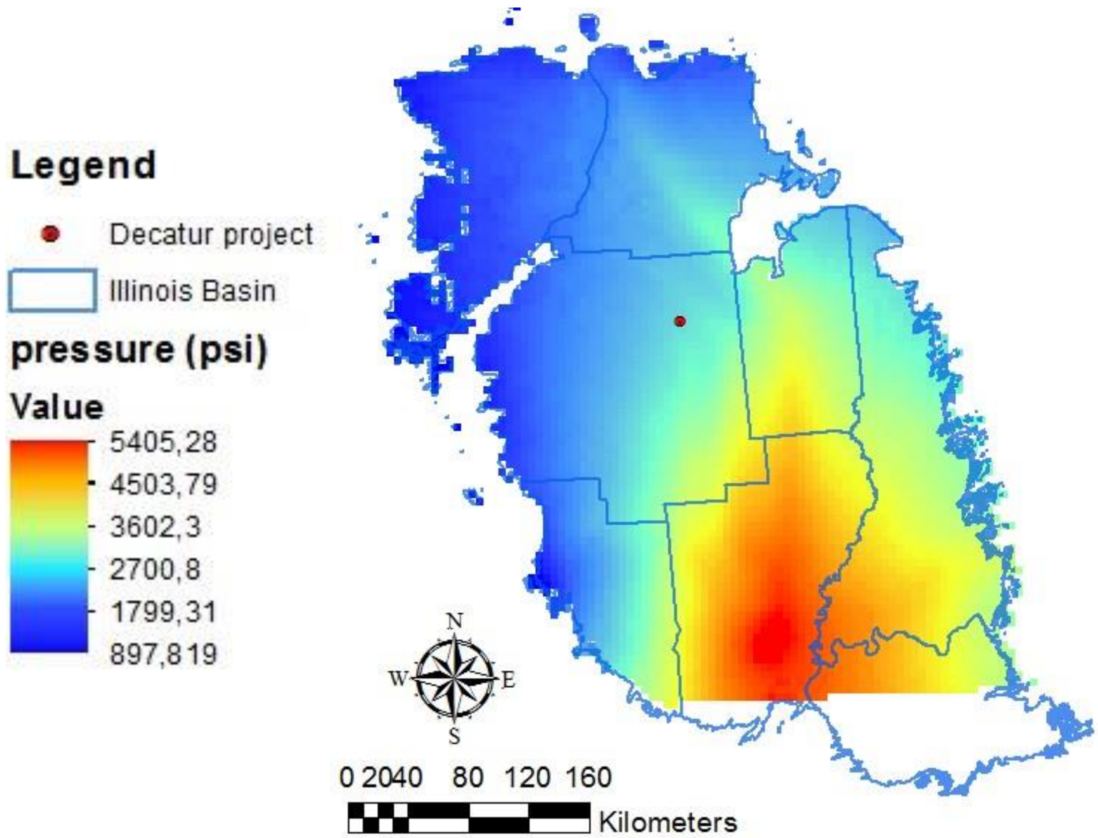

Figure 8: Pressure at the middle of the Mt. Simon Sandstone (psi)

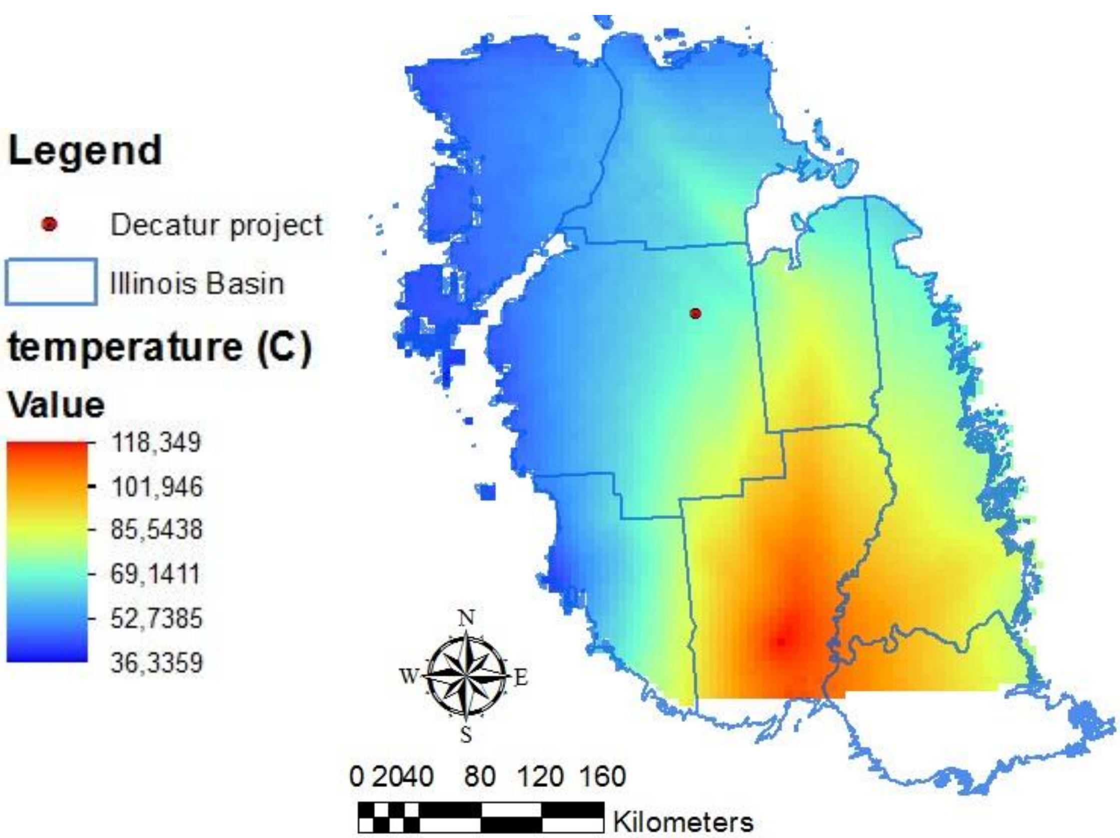

Figure 9: Temperature at the middle of the Mt. Simon Sandstone (°C)

Is it convenient?

Locations of CO2 sources within the Illinois Basin and their emissions in tons were mapped in figure 10. The original data contained eight different types of CO2 sources but in order to make the figure clearer I only showed the two most important ones. The main CO2 source is the one related to electricity (power plants). Moreover, the Decatur Project site is located at 818 meters of an ethanol factory which produced approximately 4 million tons of CO2 per year. This location has notably been chosen because of the proximity of an existing CO2 source.

I was not able to find data corresponding to the location of CO2 pipelines but this would have been interesting to see if sites further away to CO2 sources could still be conveniently used.

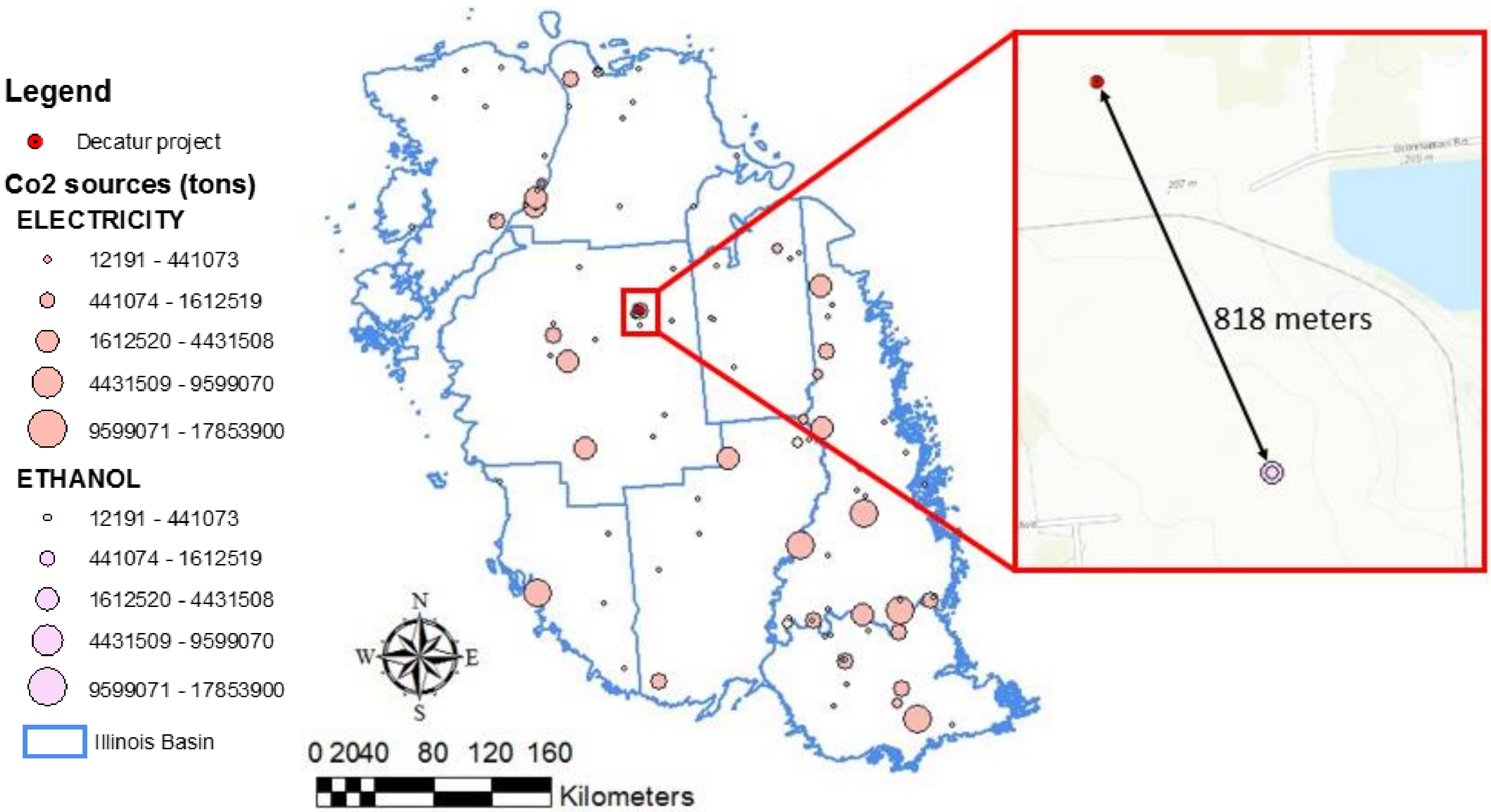

Figure 10: Location and type of CO2 sources in the Illinois basin

How much CO2 can we stored?

The mass of CO2 that can be stored underground is equal to the following equation: $M_{CO_2} = A_t h \varphi \rho_{CO_2} E_{saline}$

where $A_t = \text{reservoir area}$; h = reservoir thickness ; φ = porosity ; ρ_{CO_2} = CO2 density; E_{saline} = storage efficiency factor

The main unknowns in this equation are the reservoir thickness, the porosity and the storage efficiency factor. For this last parameter, two simulations have been done: one with a low estimate of E = 0.51% and one with a high estimate of E=5.5%. The results of those simulations are given figures 11 and 12.

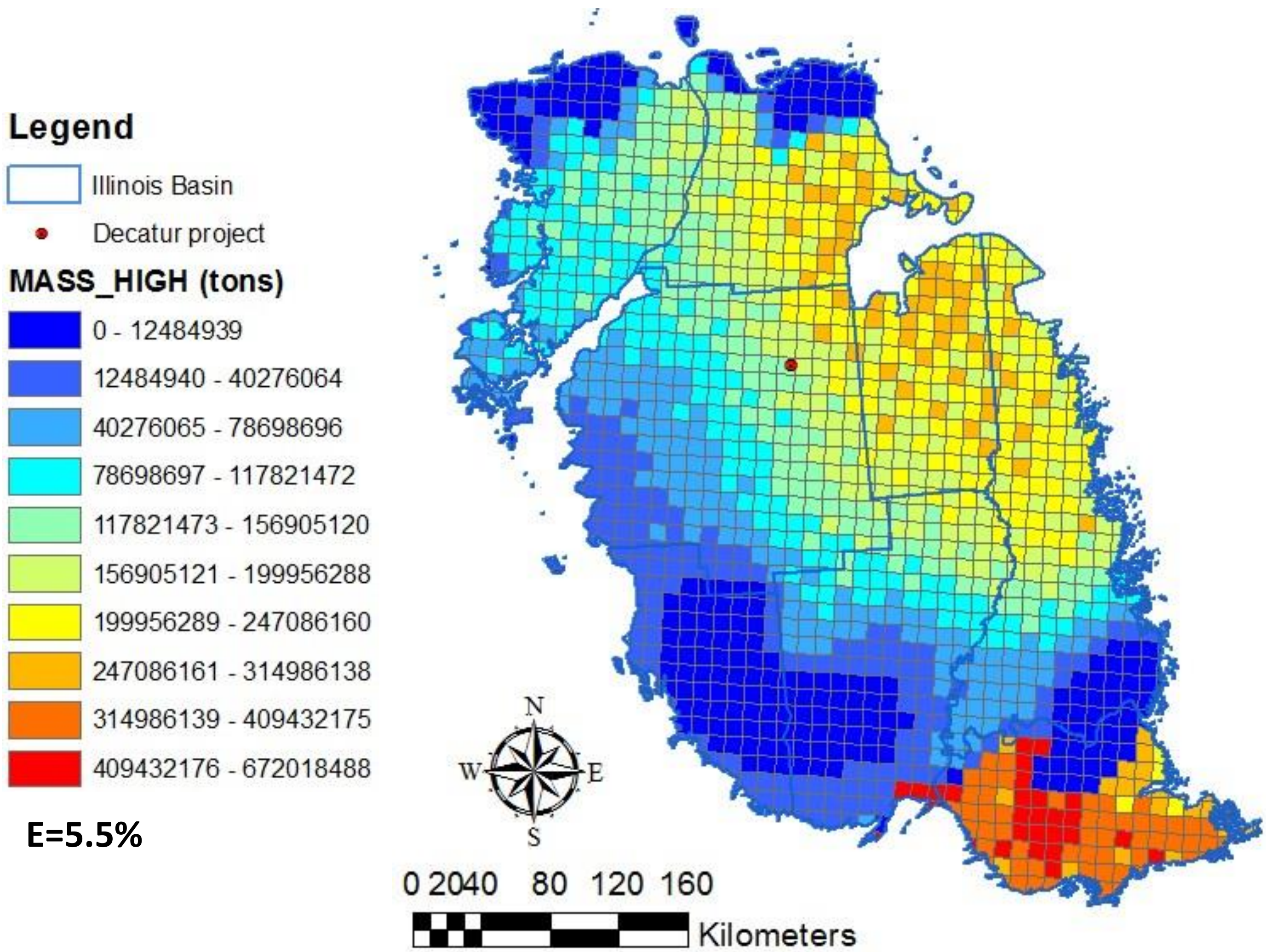

Figure 11: High estimate of CO2 storage (tons)

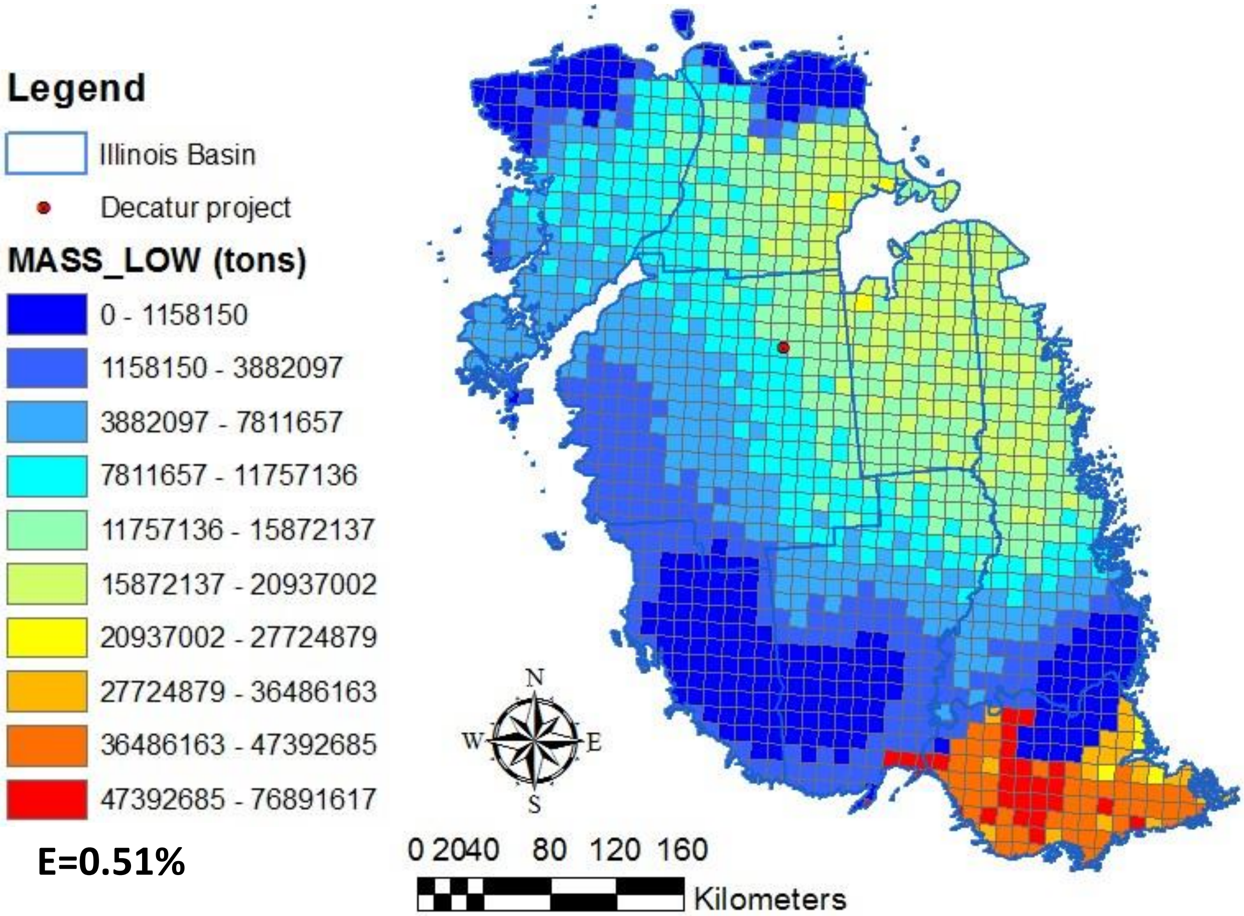

Figure 12: High estimate CO2 storage (tons)

Conclusion

The optimal conditions for GCS are summarized by order of importance in figure 13. The final result is represented in figure 14 where the green areas are the locations which meet all those criteria. The red zones and the green zones with the red stripes are the places where at least one condition is not respected. The image of the impermeable layer has been superimposed to this GIS map in order to give the final result. We were thus able to determine the areas where GCS can be realized.

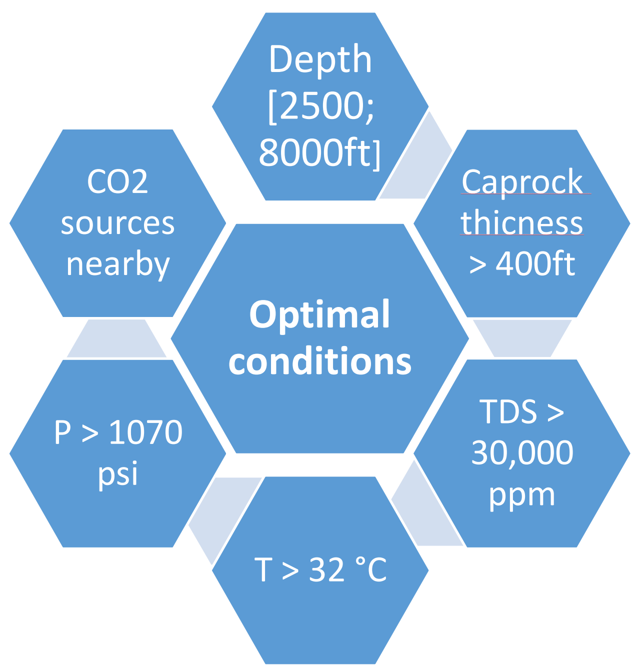

Figure 13: Optimal conditions for GCS

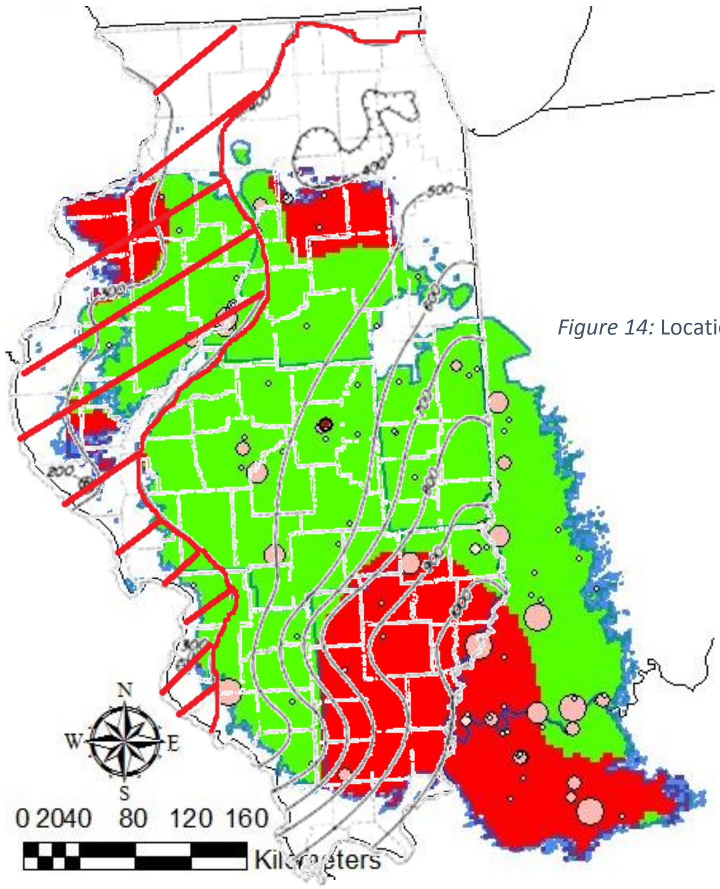

Figure 14: Locations of possible sites for GCS

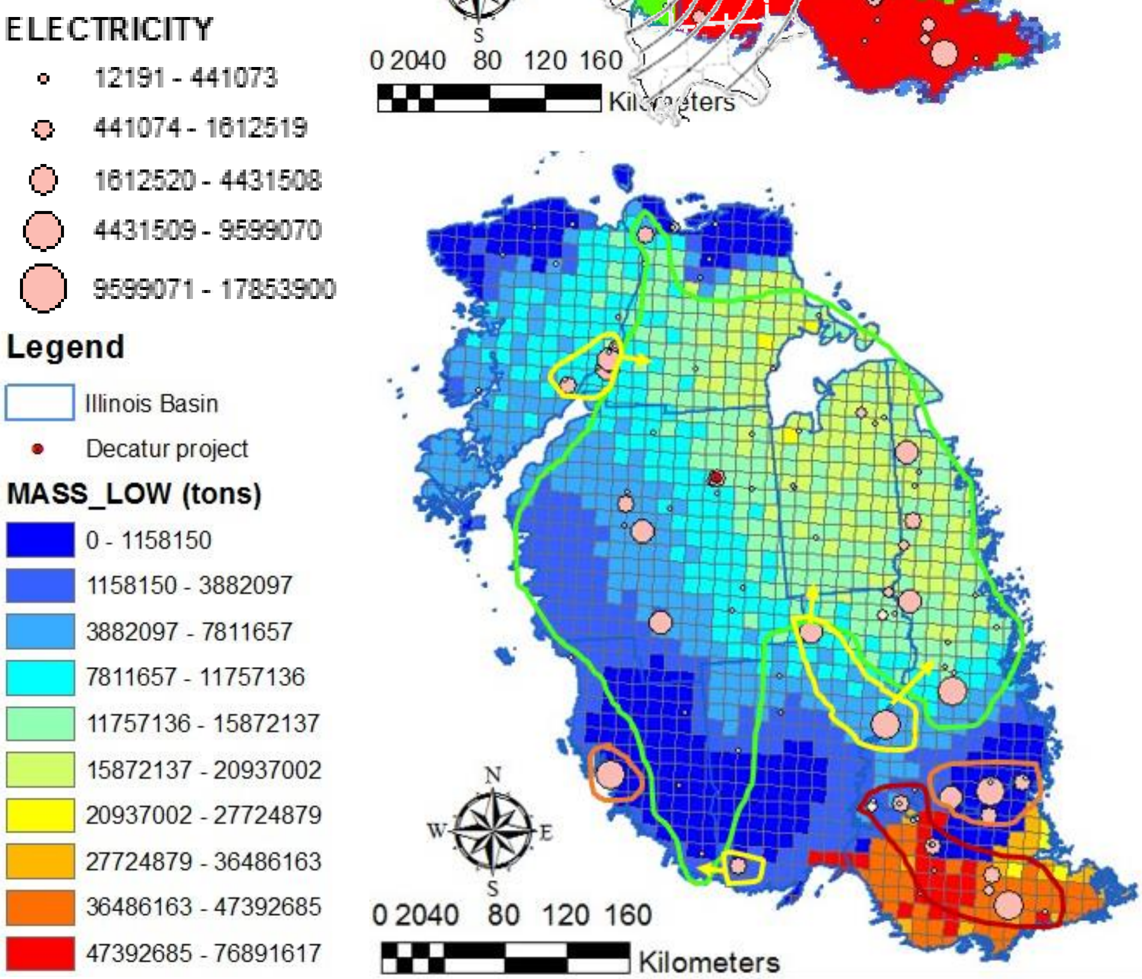

Figure 15: Compatibility of CO2 sources and sinks

We will now compare the areas where carbon sequestration is possible with the location of the CO2 sources. We will also determine whereas those locations have the necessary storage capacity for the amount of CO2 produced. We will only look at the worst case scenario where E=0.51%.

We divided the CO2 sources into four categories (*fig.15*):

- "Perfect": Depicted in green in the map where GCS is possible at this exact location and the storage capacity is greater than the emissions.
- "Need transport": Depicted in yellow where GCS is not possible at this exact location but where the CO2 source is very close to a "perfect" location.
- "Possible but not ideal": Depicted in orange where GCS is possible at this exact location but the storage capacity is inferior to the emissions.
- "Complicated": Depicted in red where GCS is not possible at this exact location and is somehow far to a "perfect" location.

Thus we can conclude that the majority of the CO2 sources in the Illinois Basin are located in "perfect" areas where carbon sequestration is possible and the sink is able to store all the emissions of CO2.

It would have been interesting to map the existing CO2 pipeline network in order to determine if the CO2 emitted from sources not far from a "perfect" location could be easily transported.

For the sources in the third categories, a more in-depth economical study should be done to assess if it is more beneficial to transport the CO2 to a "perfect" location or to store just a fraction of the total emissions on site. Here again, the pipeline grid would be needed.

Lastly, we can notice that the sources where GCS is the least favorable are located at the extreme south of the basin. It is coherent with the fact that, at this location, the Mt. Simon sandstone is replaced by the St. Peter Sandstone, which has been determined to be a worse formation to realize GCS.

Broader aspect

So we have seen through this GIS analysis that the Illinois basin has a great potential for GCS. The final table of the NATCARB atlas V present global numbers for GCS potential in Illinois and North America (*fig.16*). With approximately 1000 times more storage capacity than CO2 emissions, we can see that North American territories present a great potential for this technology.

State/ Province	CO_2 Emissions		Oil and Natural Gas Reservoirs Storage Resource			Unmineable Coal Storage Resource			Saline Formation Storage Resource			Total Storage Resource		
			Billion Metric Tons			Billion Metric Tons			Billion Metric Tons			Billion Metric Tons		
	Million Metric Tons Per Year	Number of Sources	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate
Illinois	120	231	0.10	0.20	0.34	1.45	2.38	2.87	19.68	80.75	213.07	21.23	83.33	216.28
North America Total	3,071	6,358	186	205	232	54	80	113	2,379	8,328	21,633	2,618	8,613	21,978

Figure 16: CO2 emissions and storage capacity in Illinois and North American territories

Future work

The lack of the pipeline network data was prejudicial because it was then difficult to accurately assess which sources would be easily linked to a sink. With this data we might find that some sources can be good candidates for GCS even if they are far away from a good injection site.

The permeability of the formation was also missing and it can provide another parameter in order to define the best location possible.

Lastly, one important parameter which has not been addressed at all in this paper is contact angle. Indeed, the likelihood of CO2 moving upward in the subsurface is dependent on the thickness of the impermeable layer on top of it but also on capillary pressure and contact angle. This parameter depends on the temperature, pressure, mineralogy and brine composition of the exact injection site. This phenomenon is still poorly understood by the scientific community and wasn't addressed at all in this study due to its complexity. However, it should be taken into account before any large-scale injection operation.

Sources

1. **Bureau of Economic Geology**. Sequestration of Greenhouse Gases in Brine Formations, 2012. http://www.beg.utexas.edu/gccc/CO2_data/aaBrineMain.php
2. **National Energy Technology Laboratory**. NATCARB Carbon storage atlas edition V, 2015. http://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas
3. **Illinois State Geological Survey**. http://futuregenalliance.org/pdf/FGen_EauClaire_Thickness.pdf
4. **Clean Air Task Force.** Geologic Carbon Storage: A Safe Bet, 2015. http://www.catf.us/blogs/ahead/2015/02/03/geologic-carbon-storage-a-safe-bet/
5. **Carbon Capture & Sequestration Technologies at MIT.** Decatur Fact Sheet: Carbon Dioxide Capture and Storage Project, 2015. http://sequestration.mit.edu/tools/projects/decatur.html
6. **Illinois State Geological Survey.** *Reservoir uncertainty Precambrian topography and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin*, Hannes E. Leetaru, 2009