Appendix E. Analysis of Potential Geological Sequestration of CO_2 at Five Sites in Indiana

When coal is converted to heat, syngas, and petroleum liquids, it produces a large amount of CO_2. One potential way to mitigate CO_2 emissions is to capture and store (sequester) the CO_2 produced in geological formations. In Indiana, there are essentially four types of geological formations that can be used for this purpose. They include saline-water filled reservoirs, unmineable coal seams, mature oil and gas fields, and shales rich in organic matter and gas. In the last three of these options there is a potential to create value through enhanced coal bed methane (ECBM) production, enhanced oil recovery (EOR) and enhanced shale gas recovery (EGR). These four geological settings are all present in southwestern Indiana, much of Illinois, and parts of western Kentucky, indicating potential for CO_2 sequestration in the region.

This appendix presents the results of analyses of five of the possible coal gasification sites, where the underlying geological resources were assessed for the potential to sequester produced CO_2. Each site was assessed by examining the four geological sequestration options within a 25 mile radius buffer zone centered on the site. Within southwest Indiana these sites included Crane NSA in Martin County, the Francisco coal mine in Gibson County, the Minnehaha coal mine in Sullivan County, the Merom power station in Sullivan County, and Mt. Vernon area in Posey County.

The eight primary sites analyzed in sections X-XVI of this report are contained within these five buffer zones as follows: The Breed/Fairbanks, Crane (Sullivan), Merom and Minnehaha sites are all located within the buffer zones centered on the Merom and Minnehaha sites. The CountryMark refinery and the Port of Indiana, Southwind Marine Center sites both lie within the buffer surrounding Mount Vernon. And lastly, buffer zones surrounding the Crane (Martin) and Francisco sites encompass only those sites.

E.1. CO_2 sequestration potential in the Crane NSA area, Martin County

Table E.1.1 summarizes the potential sequestration capacities in saline aquifers, mature oil and gas wells, and the New Albany shale, as well as the volumes of oil and gas (EOR and EGR) that could be produced as the result of the injection of CO_2. It is clear from this table that the most promising option for geological sequestration of CO_2 in the Crane NSA area lays in the deep saline-filled aquifers. Details of the distribution of the oil fields located to the west and north of Crane, their sequestration and EOR capabilities, and the potential of the New Albany Shale (an organic-rich gas shale), to sequester CO_2 and to produce gas as a result of CO_2 injection were included in a separate evaluation of Crane NSA completed by CCTR earlier this year (CCTR 2007), therefore a summary table and maps of the principal sequestration targets are included here. The coal seams located within the buffer area are too shallow to be used for sequestration and are therefore not included in the assessment. The maps in Figure E.2.1 illustrate the potential sequestration capacities of the Mount Simon and St. Peter sandstone saline aquifer reservoirs located within the 25 mile buffer surrounding Crane.

Table E.1.1. Potential sequestration capacities for principal geological options located within 25 miles of Crane NSA (Martin County). Also included are volumes of oil and gas that are potentially producible using injected CO_2 for enhanced recovery.

Reservoirs	CO2 Storage	Methane Recovery	Enhanced Oil/Gas Recovery
Saline Reservoirs	CO2 Storage Capacity (MMt)		
Mt. Simon Sandstone	15,355		
St. Peter Sandstone	210		
Total	15,565		
Oil & Gas	CO2 Storage Capacity (MMt)		EOR (standard barrels)
Petroleum Fields	0.67		3,828,039
Shale	CO2 Storage Capacity (MMt)	Shale Gas (MMscf)	Enhanced Shale Gas (MMscf)
New Albany Shale	572	10,004	1,500

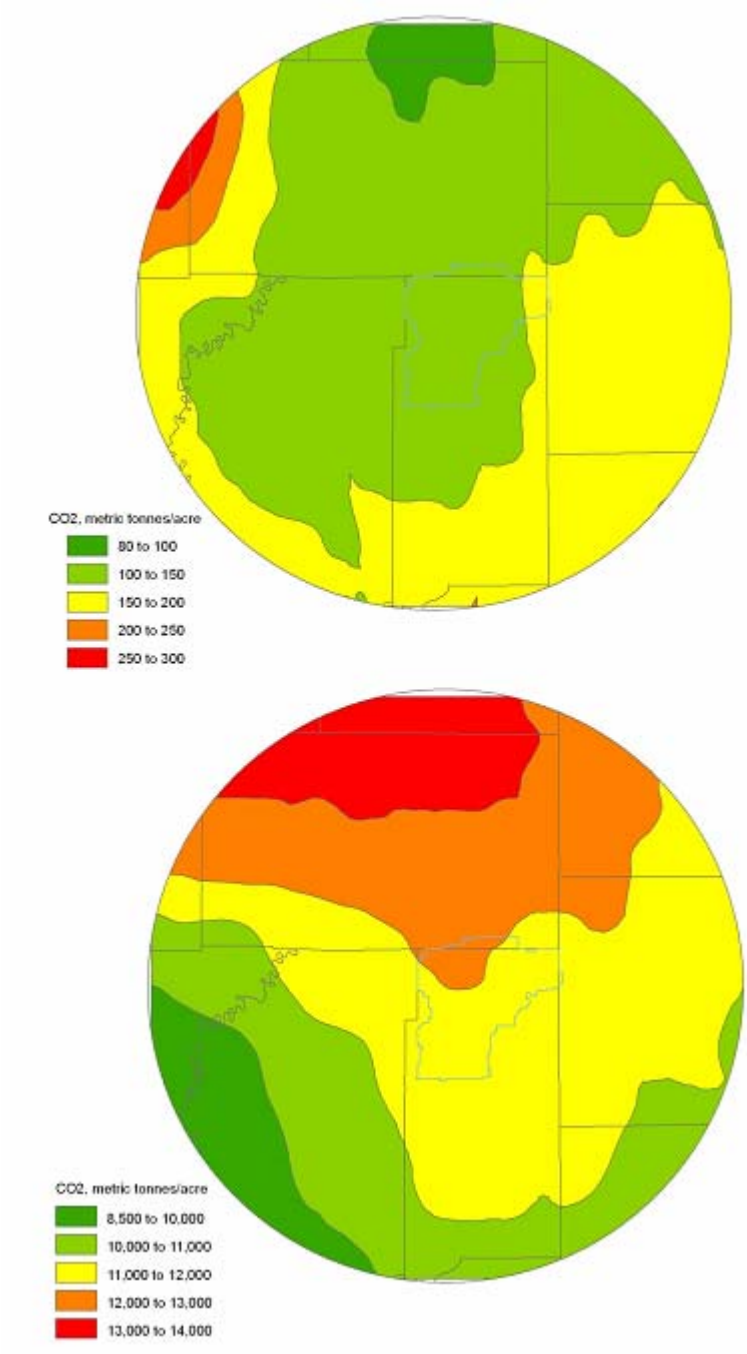


Figure E.1.1. Potential saline aquifer sequestration within a 25 mile radius of NSA Crane (Top: St. Peter sandstone; Bottom: Mt. Simon sandstone)

E.2. CO_2 sequestration potential in the Francisco mining area

Four options for the geological sequestration of CO_2 produced by a gasification facility in the Francisco area were quantitatively assessed. The results of this assessment are presented in sections E.2.1-E.2.4 below.

E.2.1. Sequestration potential in coal seams and ECBM production

The coal seams that lie within the buffer area surrounding the Francisco site are generally too shallow to be effectively utilized for sequestration of produced CO_2. Specifically, as indicated in a), b), c) and d) of Figure E.2, the potential for producing CBM and ECBM related CO_2 sequestration is minimal for both the Danville coal and the Hymera coal seams, located within about 20 miles of Francisco. Note that the radius of the circle is 25 miles, and CO_2 sequestration and ECBM is still possible for a synfuel park in Francisco if a longer pipeline is constructed for these two coals. ECBM and sequestration potentials for the Herrin, Springfield, Survant, Colchester, and Seelyville coal seams are shown in Figures E.2.1 through E.2.3, and summarized also in Table E.2.1. A total of 302,099,183 standard cubic feet (scf) of ECBM is potentially producible, and a total of 13,299,800 metric tons of CO_2 potentially sequesterable.

E.2.2. Sequestration potential in mature oil and gas fields and enhanced oil recovery (EOR)

Mature oil and gas fields located in the immediate area surrounding this site could potentially be used as sequestration reservoirs. Additionally, there is the potential for using the injected CO_2 to produce additional oil using enhanced oil recovery (EOR) techniques. In Figure E.2.5, the top circle shows a general picture of EOR potential in the area around Francisco, where the quantities are for each field are defined as an "isolated area." The figure indicates that about 10,000,000 to 57,000,000 of stock tank barrels (stb) of crude oil could be recovered from the dark green area immediately north of the Francisco mine site (indicated by a red star). There is the potential to recover as much as 212,352,317 stb of oil from the fields in the area, with the potential to sequester 47,923,701 metric tons of CO_2 in these fields.

Table E.2.1. Summary of ECBM and CO_2 sequestration potentials in the Francisco area

Francisco	**CO_2 storage potential** *(Metric tons)*	**ECBM recovery potential** *(Standard cubic feet (scf))*
Springfield	415,193	9,430,938
Seelyville	2,920,437	66,336,463
Colchester	4,230,784	96,100,425
Danville	638,037	14,492,736
Hymera	770,728	17,506,760
Herrin	656,658	14,915,695
Survant	3,667,962	83,316,166
Totals	13,299,800	302,099,183

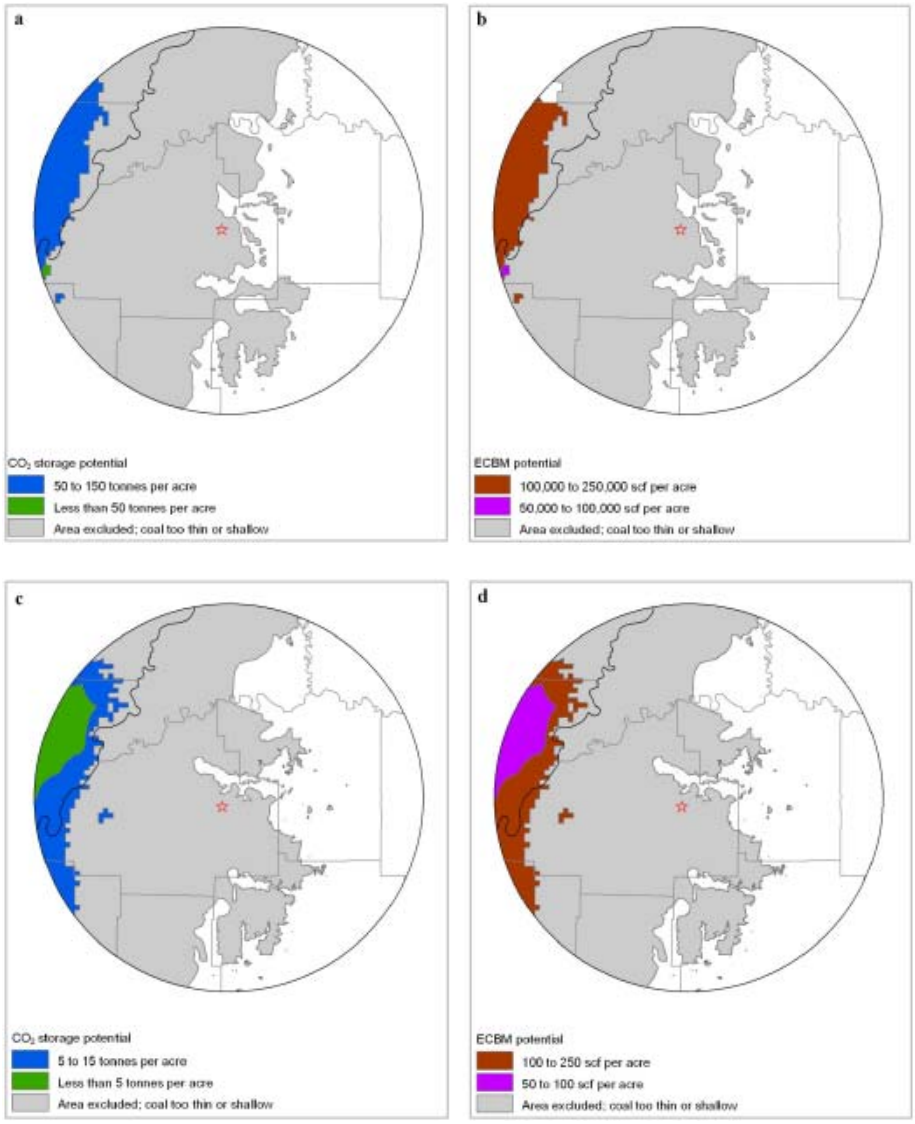


Figure E.2.1. a) & b), CO_2 sequestration and ECBM potentials for the Danville Coal; c) & d), CO_2 Sequestration and ECBM potentials for the Hymera Coal

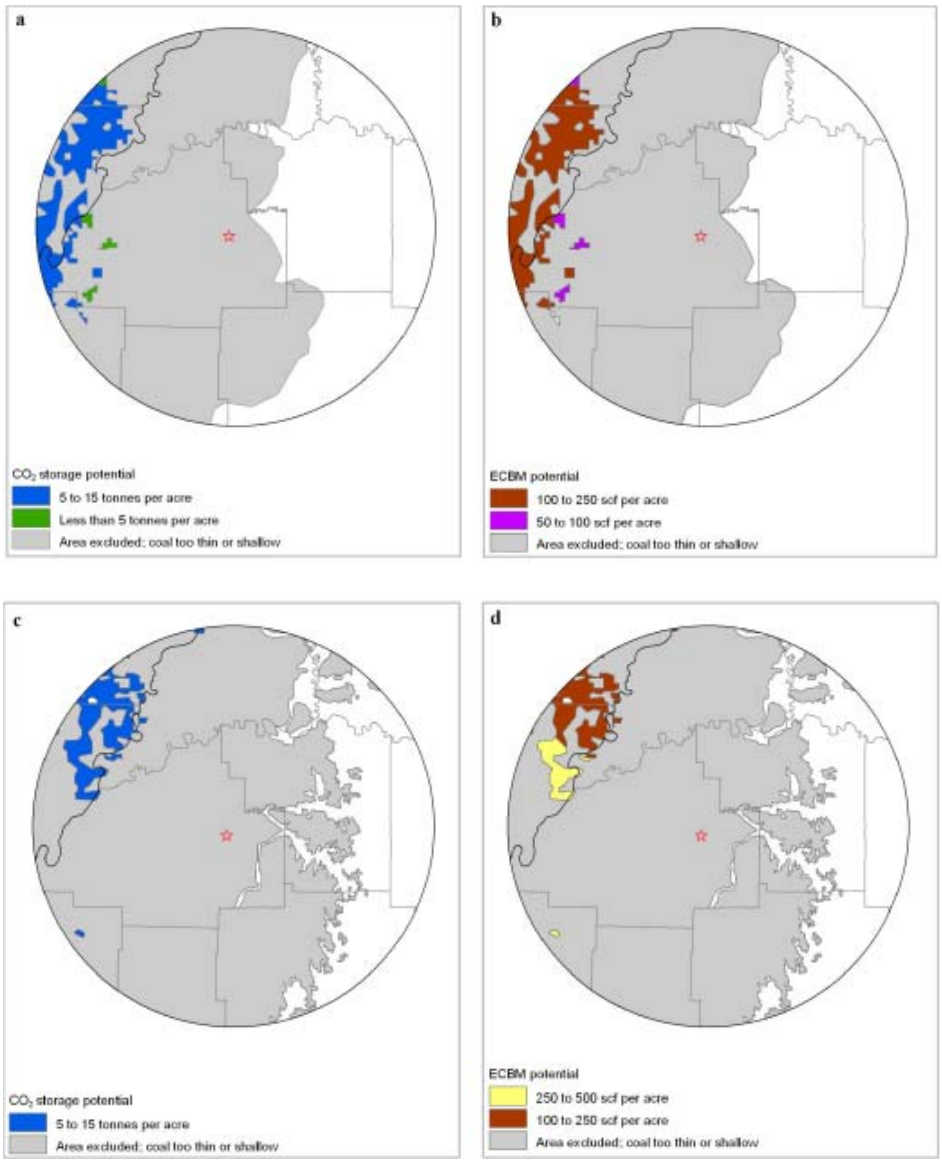


Figure E.2.2. a) & b), CO_2 sequestration and ECBM potentials for the Herrin Coal; c) & d), CO_2 Sequestration and ECBM potentials for the Springfield Coal

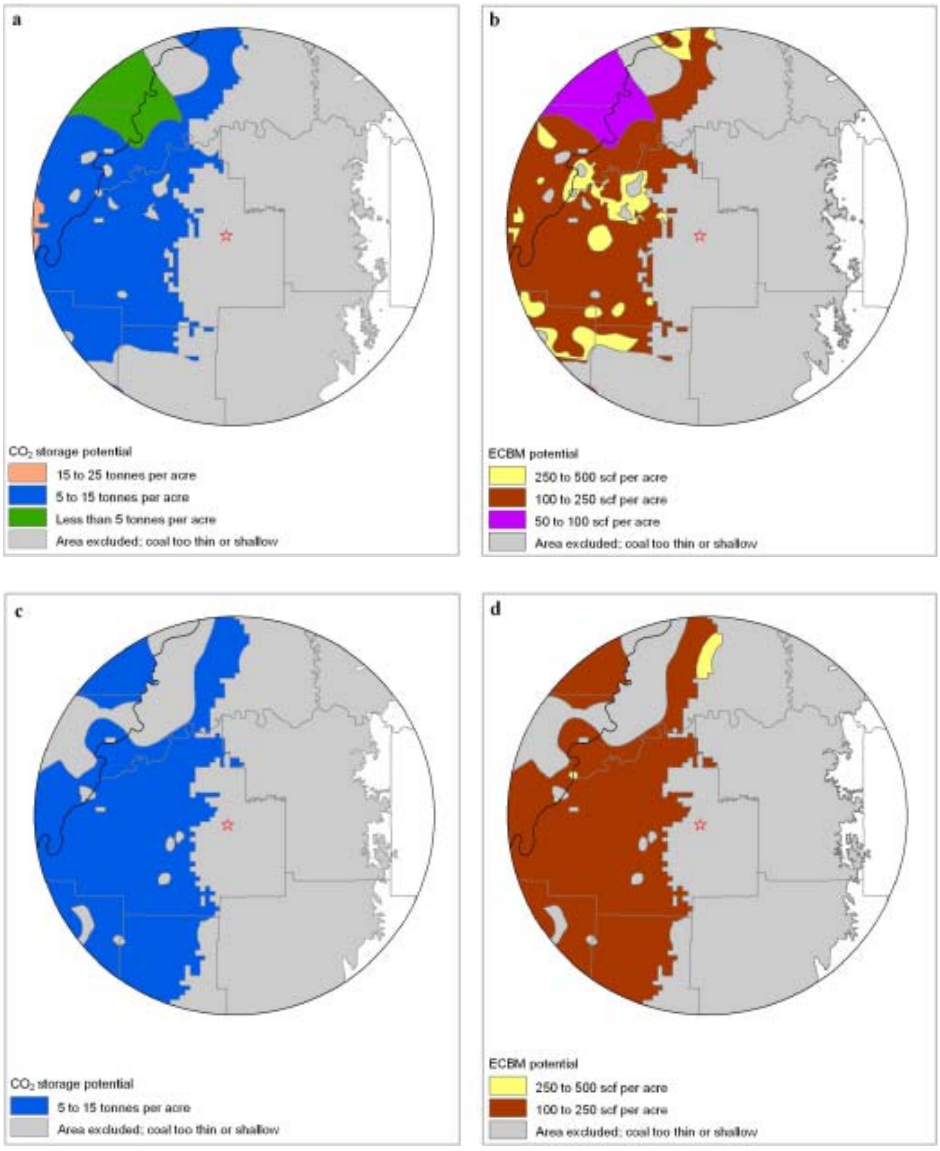


Figure E.2.3. a) & b), CO_2 sequestration and ECBM potentials for the Survant Coal; c) & d), CO_2 Sequestration and ECBM potentials for the Colchester Coal

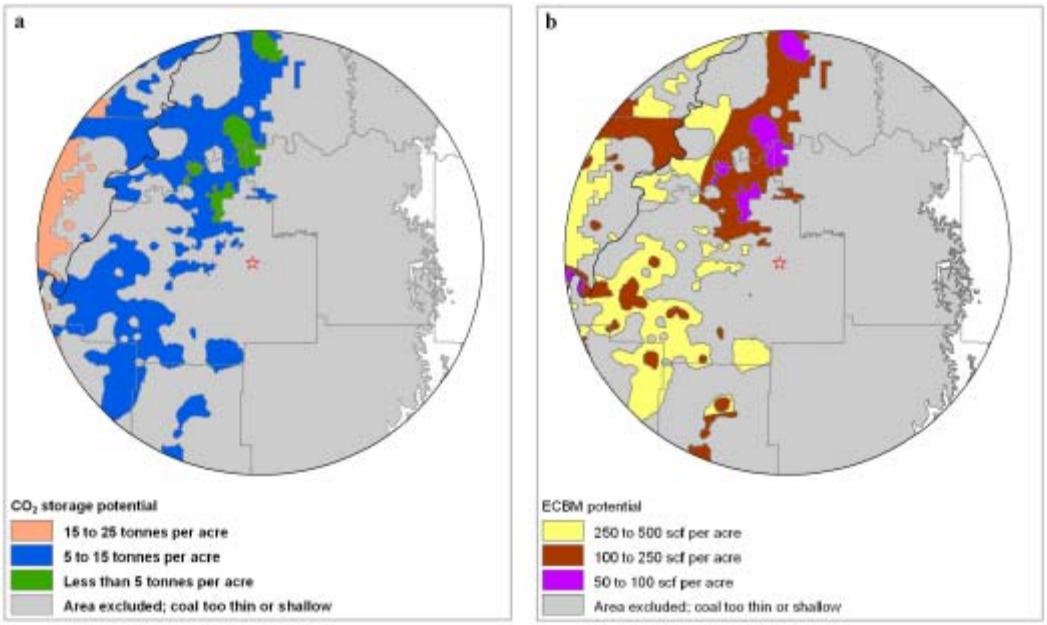
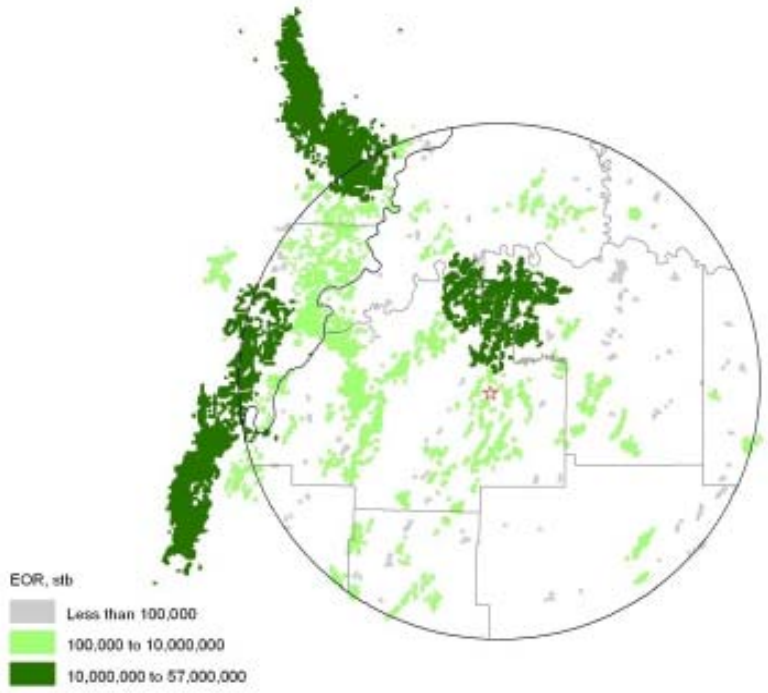


Figure E.2.4. a) & b), CO_2 sequestration and ECBM potentials for the Seelyville Coal



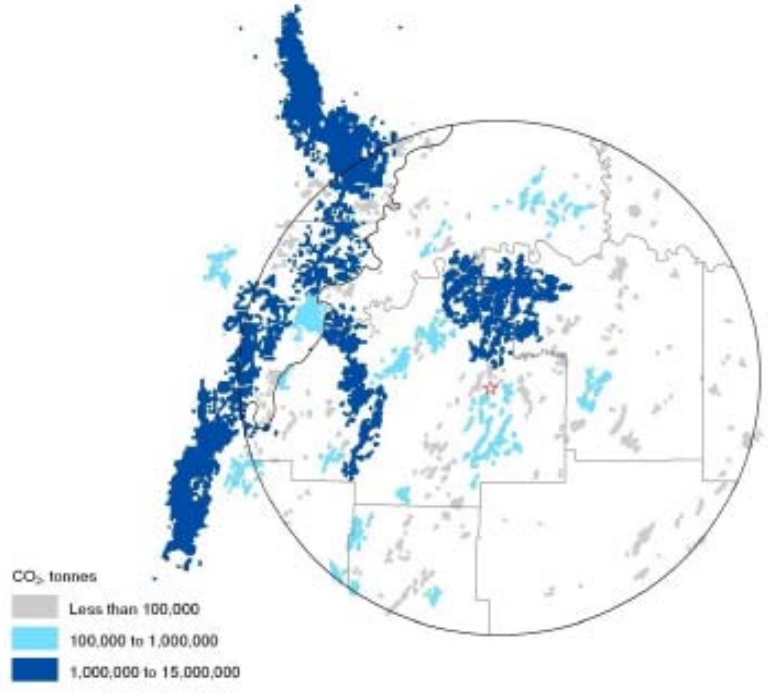


Figure E.2.5. EOR and CO_2 sequestration potential in mature oil and gas fields in the Francisco area

E.2.3. Sequestration potential in the New Albany Shale and enhanced gas recovery (EGR)

The New Albany Shale, an organic-rich gas shale, underlies all of southwestern Indiana, including the Francisco site. The potential for this unit to serve as a reservoir for injected CO_2 as well as to produce gas is described in the following figures. The New Albany Shale is a proven producer of natural gas (shale gas or SG) in Indiana. The potential for enhanced gas recovery (EGR) production also exists. These potentials are shown in Figure E.2.6. Altogether, about 2,626,037,963 scf of shale gas could potentially be recovered with the flooding of about 1,001,956,031 metric tons of CO_2. The depth and thickness of the shale gas deposits in the area are shown in Figure E.2.7.

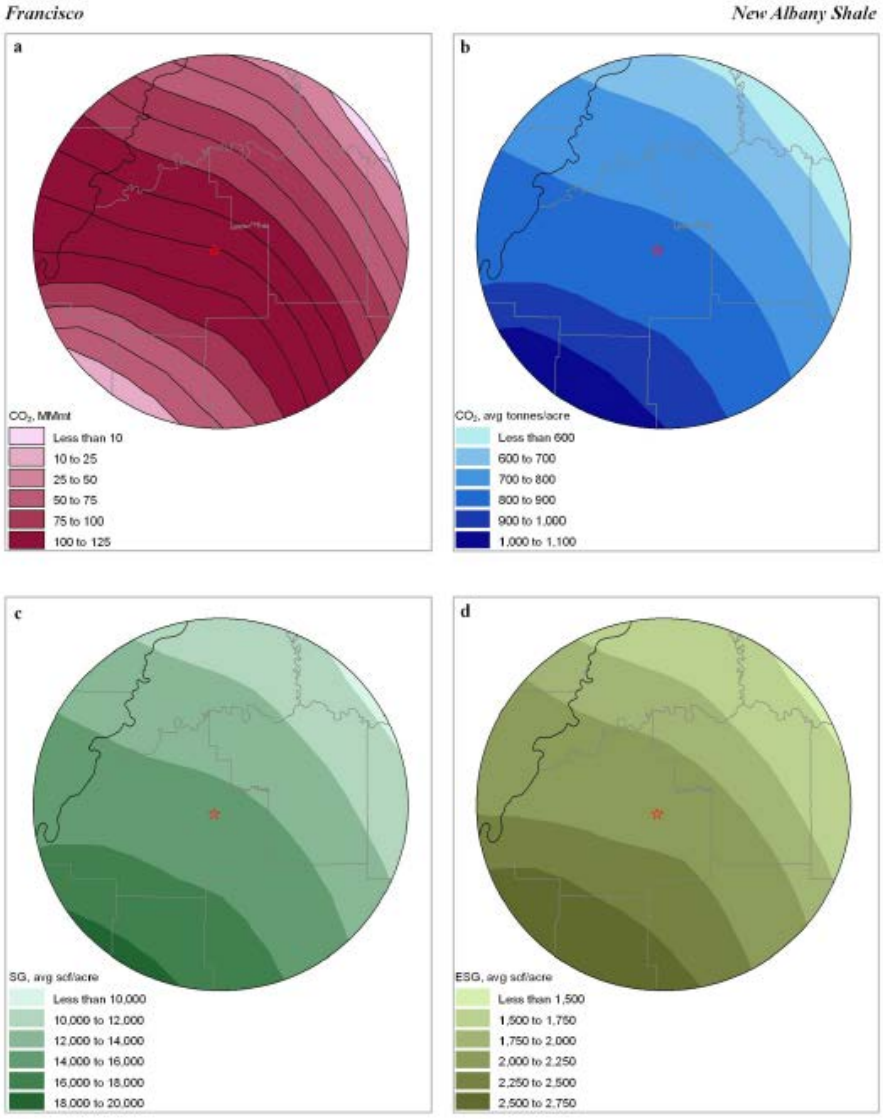


Figure E.2.6. Maps showing a) the CO_2 sequestration potential in the New Albany Shale in millions of tons in the Francisco Area: b) sequestration potential in tons/acre; c) SG production in scf/acre, and d) EGR potential in scf/per acre

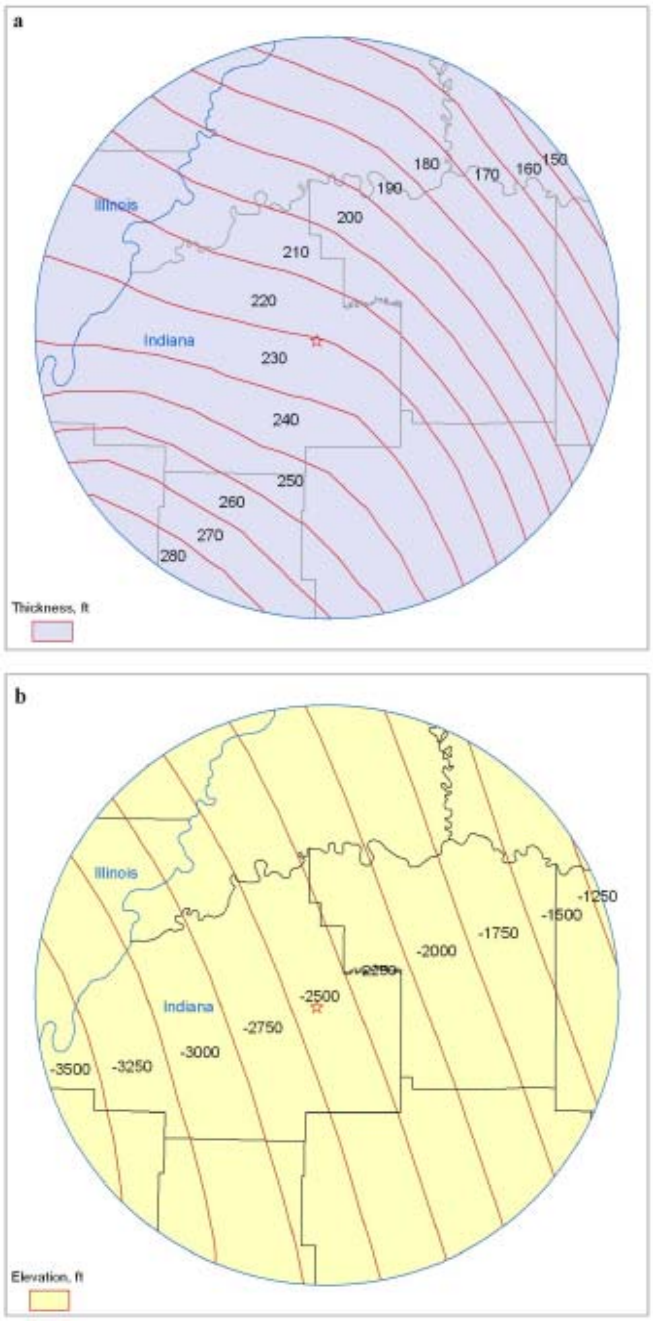


Figure E.2.7. a) Thickness, b) subsea elevation of the New Albany shale in the Francisco area

E.2.4. Sequestration potential in saline water-filled aquifers

The potential to use a deep saline water-filled aquifer as a reservoir for injected CO_2 also exists at the Francisco site. In contrast with the two northern sites in which the Cambro-Orovician Mount Simon Sandstones are assessed as potential reservoirs, only the Knox Supergroup was assessed in the southern two sites (Francisco and Mount Vernon). The results of that analysis are shown in Figure E.2.8. The map on the left side of the illustration shows the sequestration potential of the unit by displacement of the saline water by CO_2 injected into the Knox aquifer, while the right side of the diagram represents the sequestration potential by dissolution into saline fluids in the same formation. The combined CO_2 sequestration potential is about 414,218,166 metric tons.

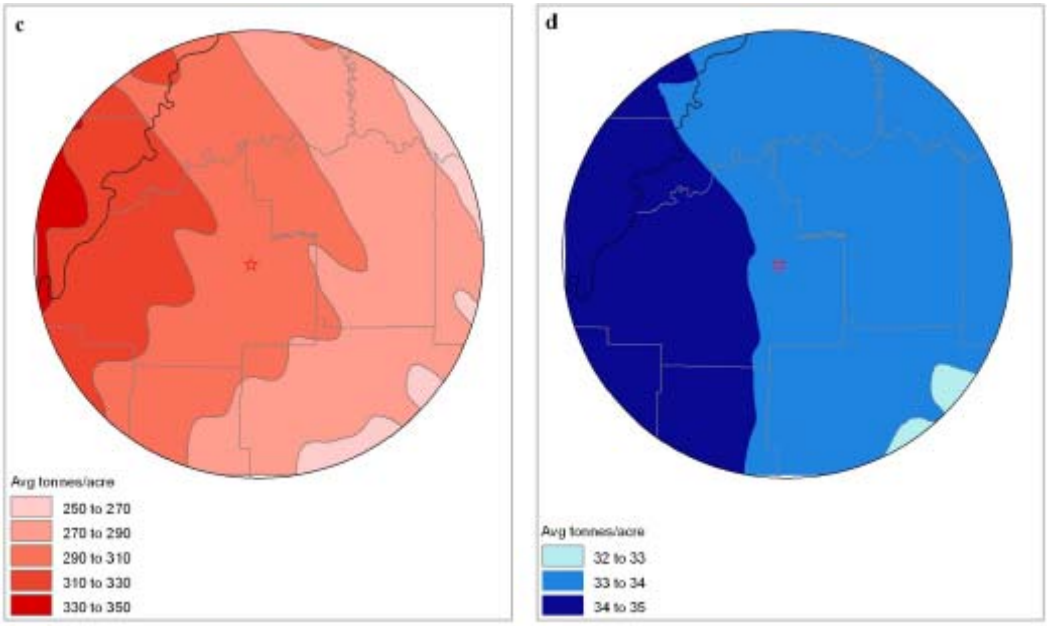


Figure E.2.8. c) Displacement sequestration potential in the Knox Supergroup saline aquifer, d) dissolution sequestration potential in the same formation (in tons/acre)

E.3. CO_2 sequestration potential in the Merom area

There are four potential options for geological sequestration of CO_2 from a gasification facility at the Breed/Fairbanks brownfield site, at the western Crane NSA site near Sullivan City, or at the Merom mining area. The results of this quantitative assessment are presented in sections E.3.1-E.3.4 below.

E.3.1. Sequestration potential in coal seams and ECBM production

The Danville, Hymera, Herrin, and Springfield coal seams that lie within the part of Indiana surrounding the Merom site and within 10 miles of the Merom area are too shallow to be effectively utilized for sequestration of CO_2, as indicated in Figures E.3.1 and E.3.2. Therefore, the potential for CBM production and ECBM recovery related CO_2 sequestration in these coal seams is limited. ECBM and sequestration potentials for the Survant, Colchester, and Seelyville coals are shown in Figures E.3.2 through E.3.4, and summarized also in Table E.3.1, with a total of 497,657,733 scf of ECBM, and a total of 21,909,190 metric tons of CO_2 storage potential. The other sites within the buffer zone (Breed/Fairbanks and Crane

Sullivan) are on the north east sides of these circles where the coal seams are generally too thin for ECBM production and related CO_2 sequestration.

Table E.3.1. CO_2 sequestration and ECBM in Merom

Merom	**CO_2 storage potential** *(Metric tons)*	**ECBM recovery potential** *(Standard cubic feet (scf))*
Springfield	415,193	9,430,938
Seelyville	2,920,437	66,336,463
Colchester	4,230,784	96,100,425
Danville	638,037	14,492,736
Hymera	770,728	17,506,760
Herrin	656,658	14,915,695
Survant	3,667,962	83,316,166
Totals	13,299,800	302,099,183

E.3.2. Sequestration potential in mature oil and gas fields and enhanced oil recovery (EOR)

Both the potential for using mature oil and gas fields located within 10-15 miles of the Merom area as sequestration reservoirs and the related potential for using the injected CO_2 to produce additional oil using enhanced oil recovery (EOR) techniques are limited. The top circle in Figure E.3.5 shows a general picture of EOR potential around the area, where the quantities are for each field defined as an "isolated area." Based on this figure, it appears that about 100,000 to 10,000,000 stock tank barrels (stb) of crude oil could be recovered from the light green areas a few miles east of Merom inside Indiana. More EOR potential is possible across the border in Illinois, about 10 miles west of Breed/Fairbanks and Merom. However, that area is not included in the estimates listed here. The estimated potential for EOR oil production is 157,733,088 stb, and the CO_2 sequestration potential is 27,983,570 tons. Within Indiana, the potential at the other sites within the Merom buffer zone (Breed/Fairbanks and Crane Sullivan) is similarly limited.

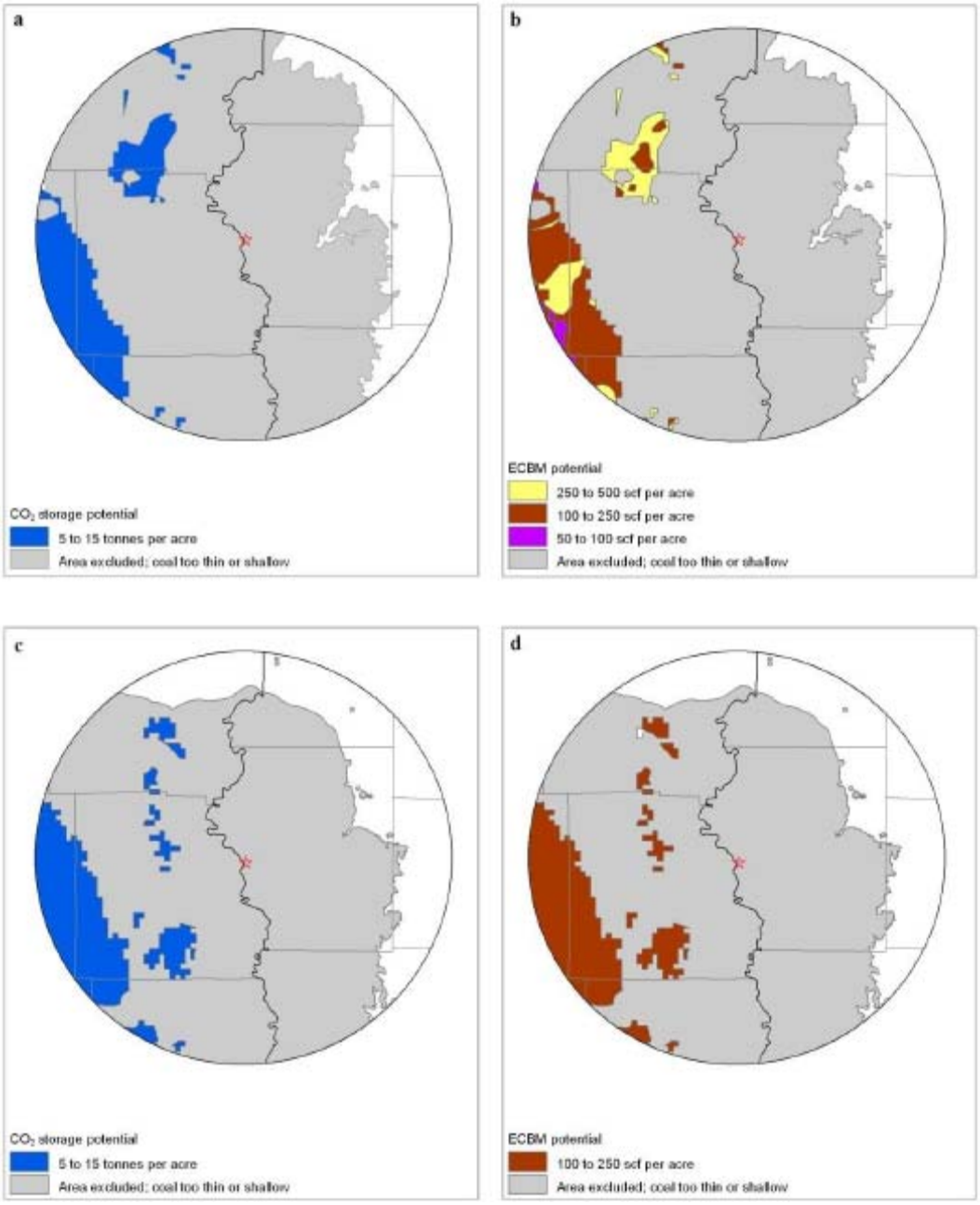


Figure E.3.1. a) & b), CO_2 sequestration and ECBM potentials of the Danville Coal; c) & d), CO_2 sequestration and ECBM potentials of the Hymera Coal near Merom

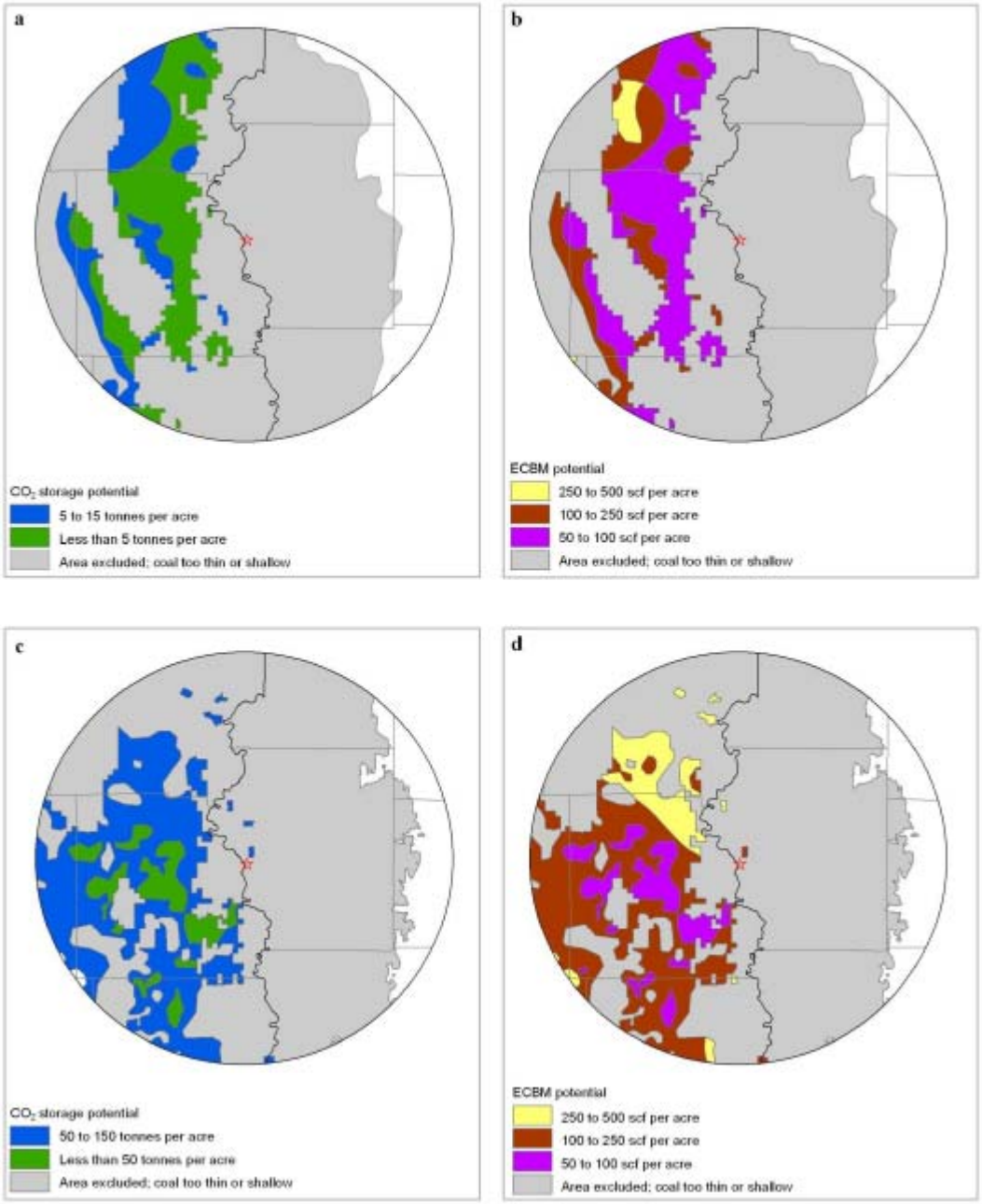


Figure E.3.2. a) & b), CO_2 sequestration and ECBM potentials of the Herrin Coal; c) & d), CO_2 sequestration and ECBM potentials of the Springfield Coal near Merom

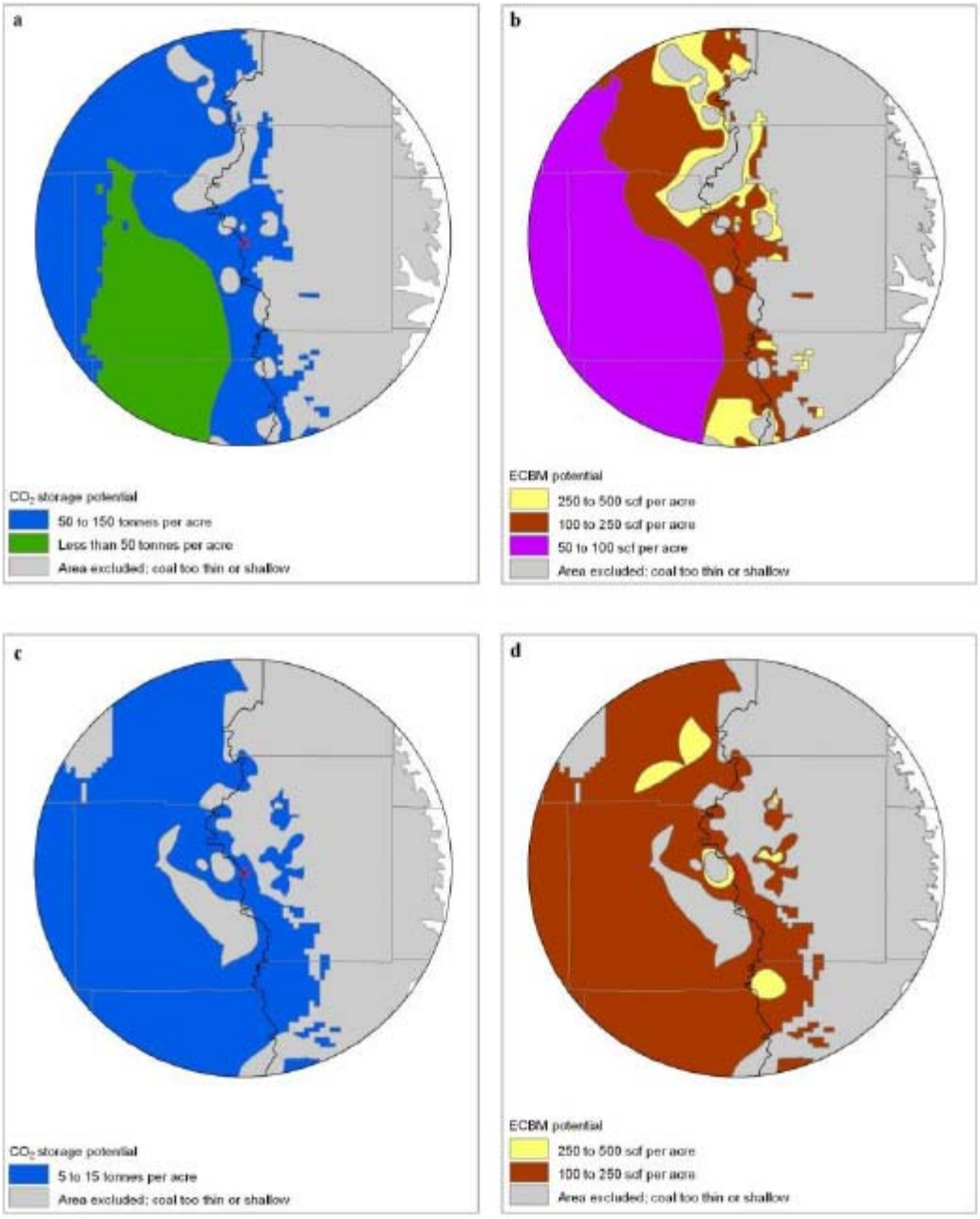


Figure E.3.3. a) & b), CO_2 sequestration and ECBM potentials of the Survant Coal; c) & d), CO_2 sequestration and ECBM potentials for the Colchester Coal

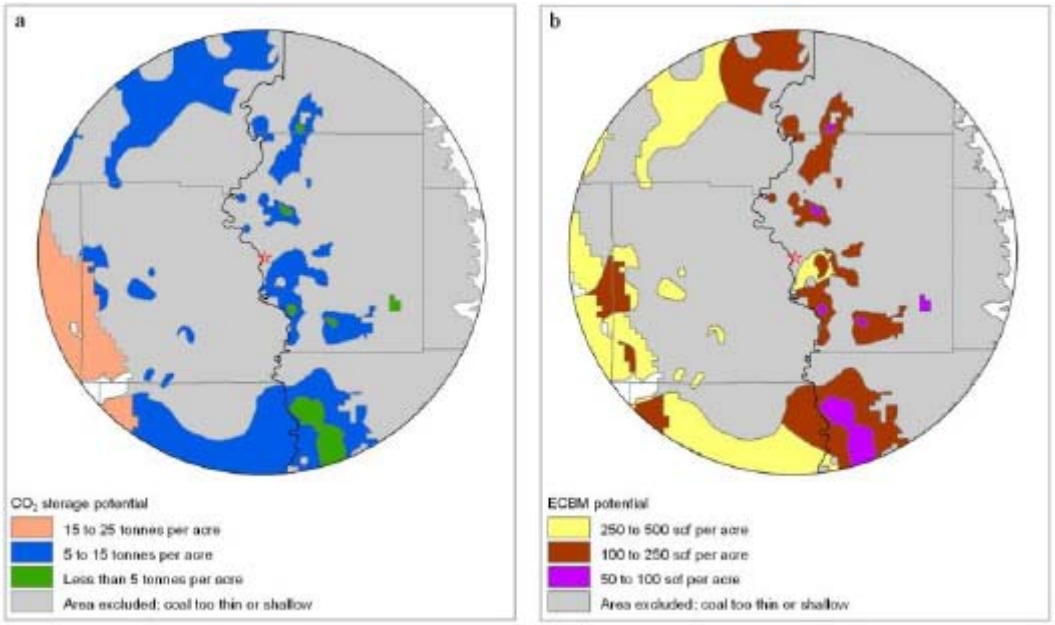
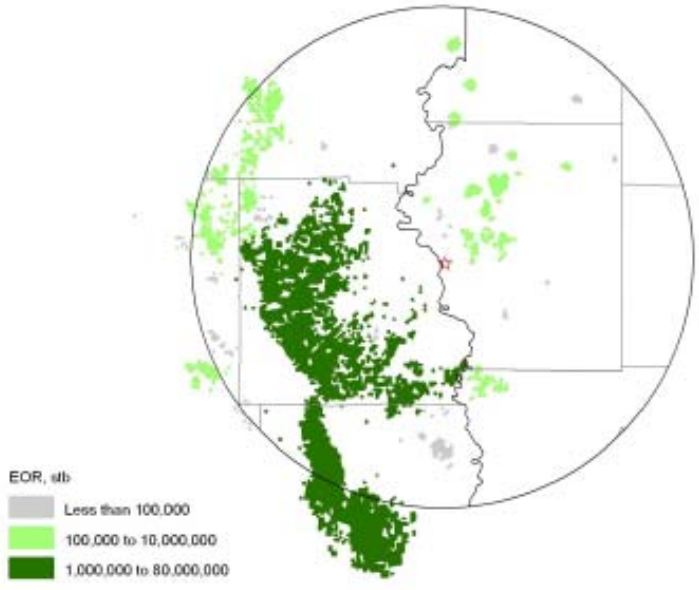


Figure E.3.4. a) & b), CO_2 sequestration and ECBM potentials of the Seelyville Coal



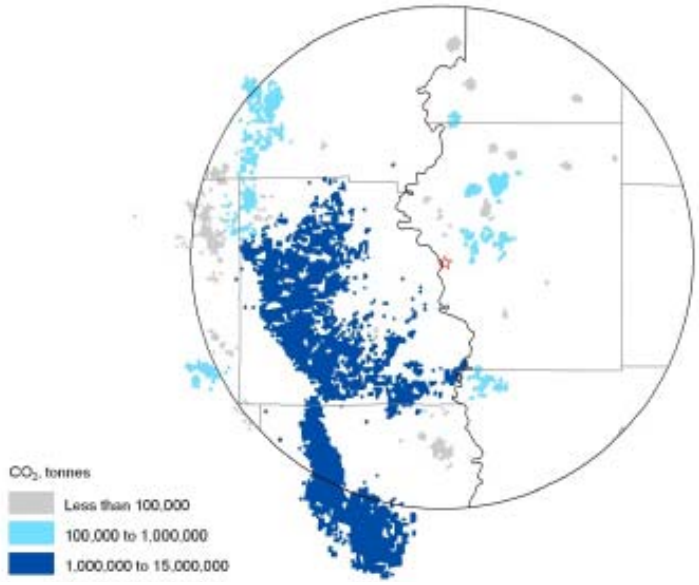


Figure E.3.5. EOR and CO_2 sequestration potential in mature oil and gas fields in the Merom area

E.3.3. Sequestration potential in the New Albany Shale and enhanced gas recovery (EGR)

The New Albany Shale, an organic-rich gas shale, underlies all of southwestern Indiana, including the buffer zone surrounding the Merom area. The potential for this feature to serve as a reservoir for injected CO_2 as well as producing gas is described in the following figures. The New Albany Shale is a proven producer of natural gas (shale gas or SG) in Indiana. There exists the potential for enhanced gas recovery (EGR) production. These potentials are shown in Figure E.3.6. Altogether, about 1,622,038,906 scf of shale gas could potentially be recovered with the flooding of about 618,883,538 metric tons of CO_2. The

depth and thickness of the shale gas deposits in the area are shown in Figure E.3.7. The potential at the other sites within the Merom buffer zone (Breed/Fairbanks and Crane Sullivan) is similar.

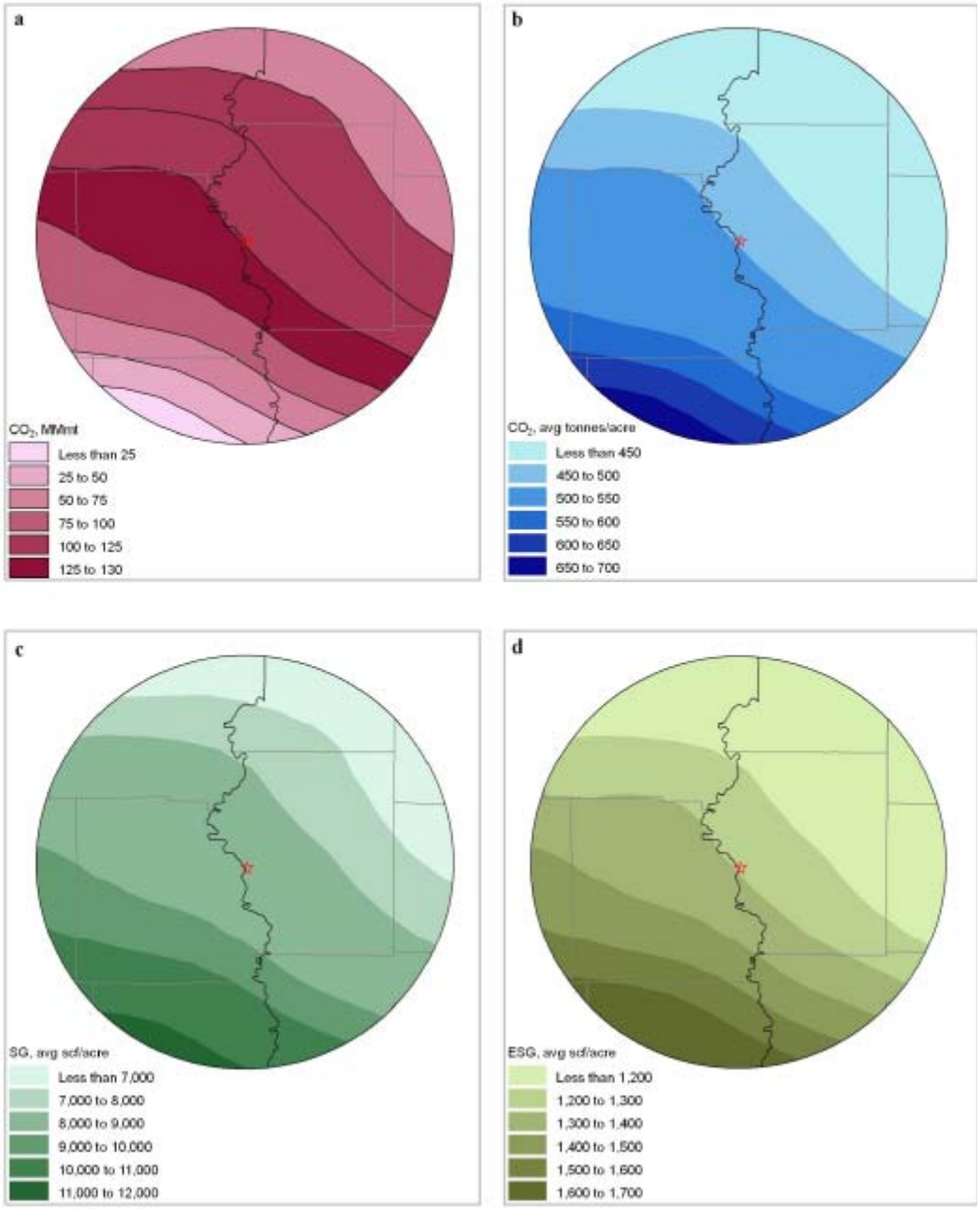


Figure E.3.6. a) CO_2 sequestration in million tons in the area: b) average tons/acre; c) SG scf/acre, d) EGR per acre

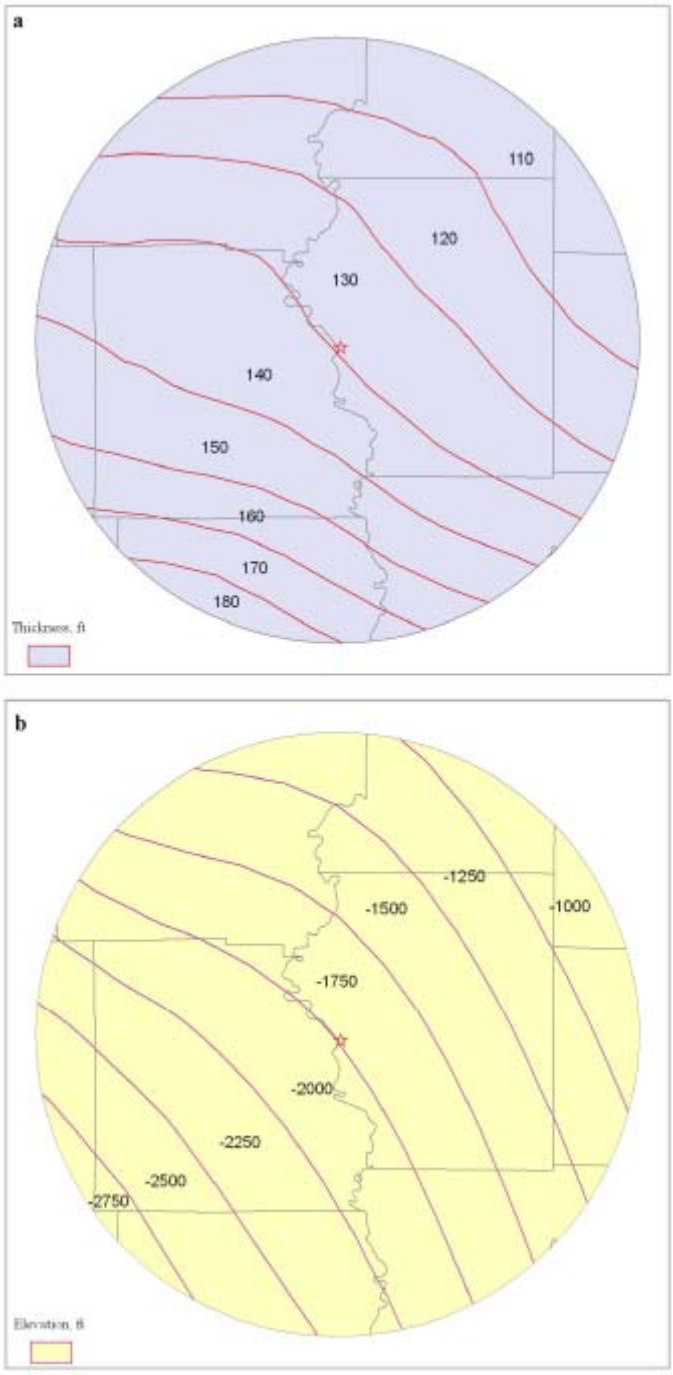


Figure E.3.7. a) Thickness, b) subsea elevation of the New Albany shale in the Merom area

E.3.4. Sequestration potential in saline water-filled aquifers

The potential to use a deep saline water-filled aquifer as a reservoir for injected CO_2 also exists within the Merom buffer zone. The Cambro-Orovician Mount Simon Sandstones are assessed as potential reservoirs, and the results are shown in Figure E.3.8. The map on the left side of the illustration shows the sequestration potential of the unit by displacement of the saline water by injected CO_2 into the aquifer, while the right side of the diagram represents the sequestration potential by dissolution into saline fluids in the same formation. The CO_2 sequestration potential is about 15,15,518,120,342 tons.

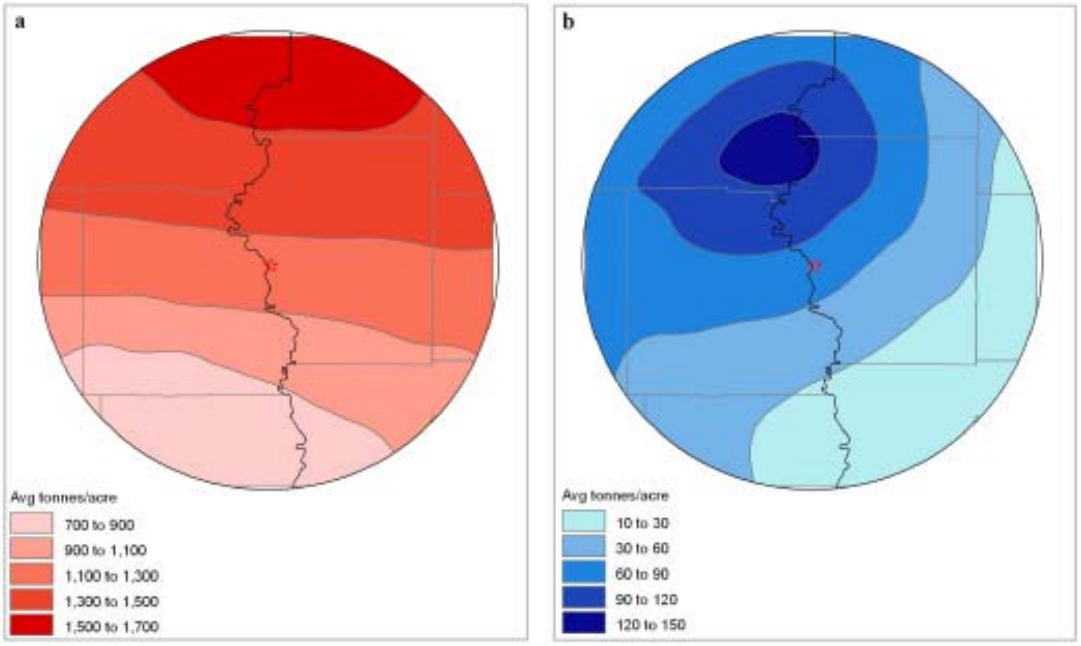


Figure E.3.8. a) Displacement sequestration potential in the Mt. Simon Sandstone aquifer, b) displacement sequestration potential in the same formation

E.4. CO_2 sequestration potential in the Mt. Vernon area

Four potential options for geological sequestration of CO_2 from a gasification facility in the Mt. Vernon area were quantitatively assessed. The results of this assessment are presented in sections E.4.1-E.4.4 below.

E.4.1. Sequestration potential in coal seams and ECBM production

The coal seams that lie within 8 miles of the Mt. Vernon site (the Danville, Hymera, Herrin, and Springfield coal seams) are too shallow to be effectively utilized for sequestration of CO_2, as indicated in Figures E.4.1 and E.4.2. Therefore, the potential for ECBM and ECBM related CO_2 for local sequestration in these coal seams is limited. ECBM and sequestration potentials for the Survant, Colchester, and Seelyville coals are shown in Figures E.4.3 through E.4.4, and summarized also in Table E.4.1. The total is 683,054,225 scf of ECBM, and a total of 30,071,200 metric tons of CO_2 storage potential.

Table E.4.1. CO_2 sequestration and ECBM in Mt. Vernon

Mt. Vernon	**CO_2 storage potential** *(Metric tons)*	**ECBM recovery potential** *(Standard cubic feet (scf))*
Springfield	2,034,915	46,222,210
Seelyville	8,930,528	202,853,070
Colchester	5,144,243	116,849,239
Danville	3,511,551	79,763,356
Hymera	1,339,680	30,430,248
Herrin	1,533,796	34,839,505
Survant	7,576,486	172,096,596
Totals	30,071,200	683,054,225

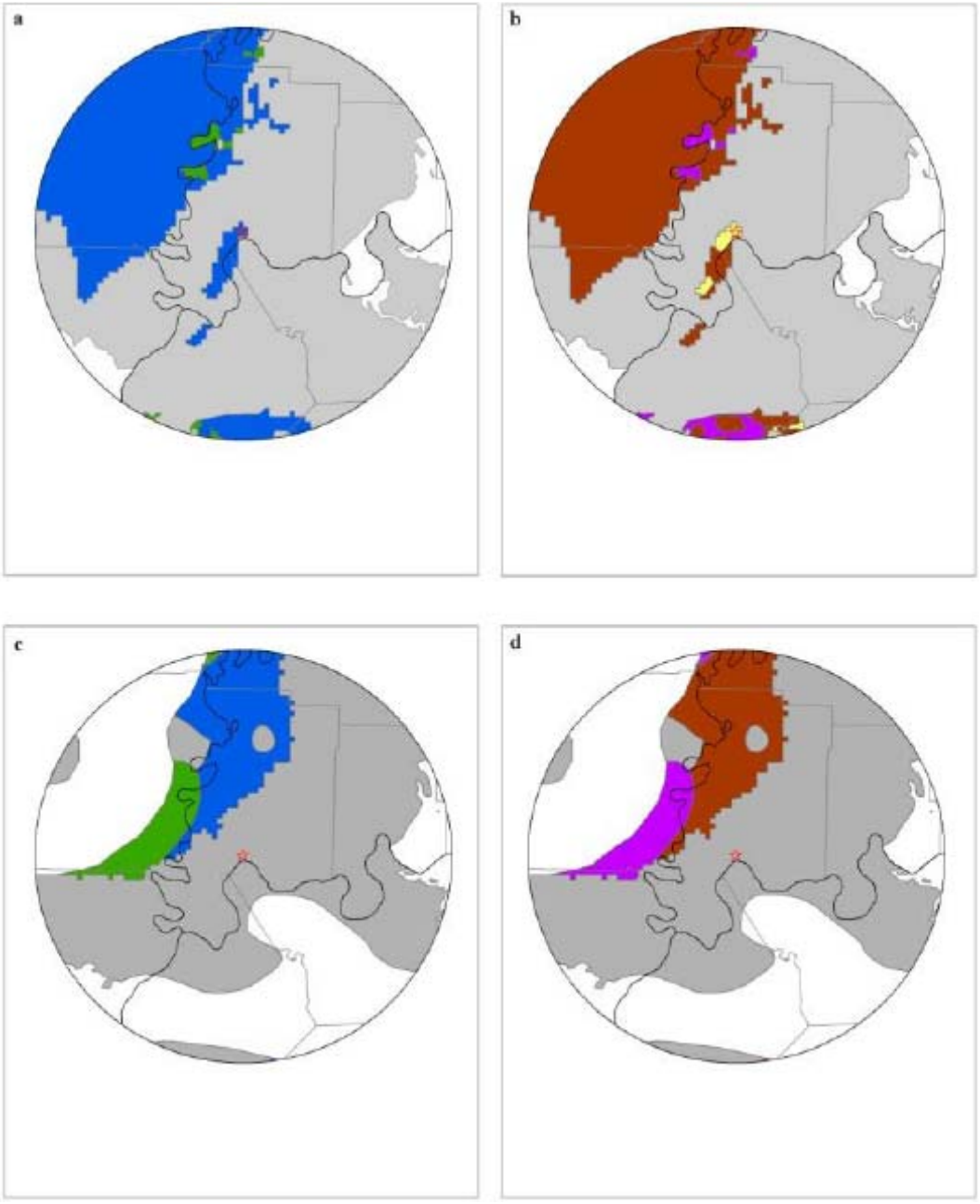


Figure E.4.1. a) & b), CO_2 sequestration and ECBM potentials of the Danville Coal; c) & d), CO_2 sequestration and ECBM potentials of the Hymera Coal in Mt. Vernon

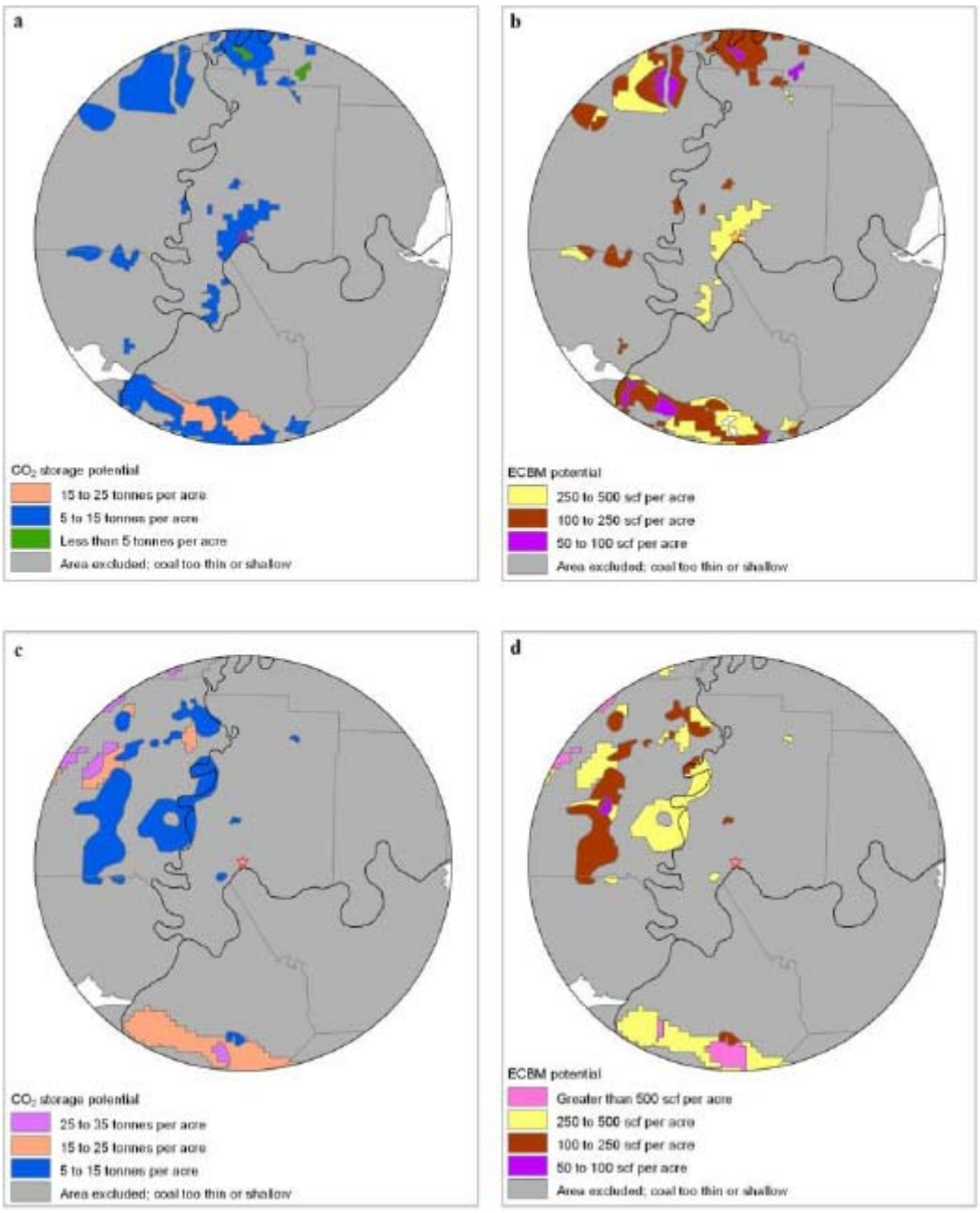


Figure E.4.2. a) & b), CO_2 sequestration and ECBM potentials of the Herrin Coal; c) & d), CO_2 sequestration and ECBM potentials of the Springfield Coal in Mt. Vernon

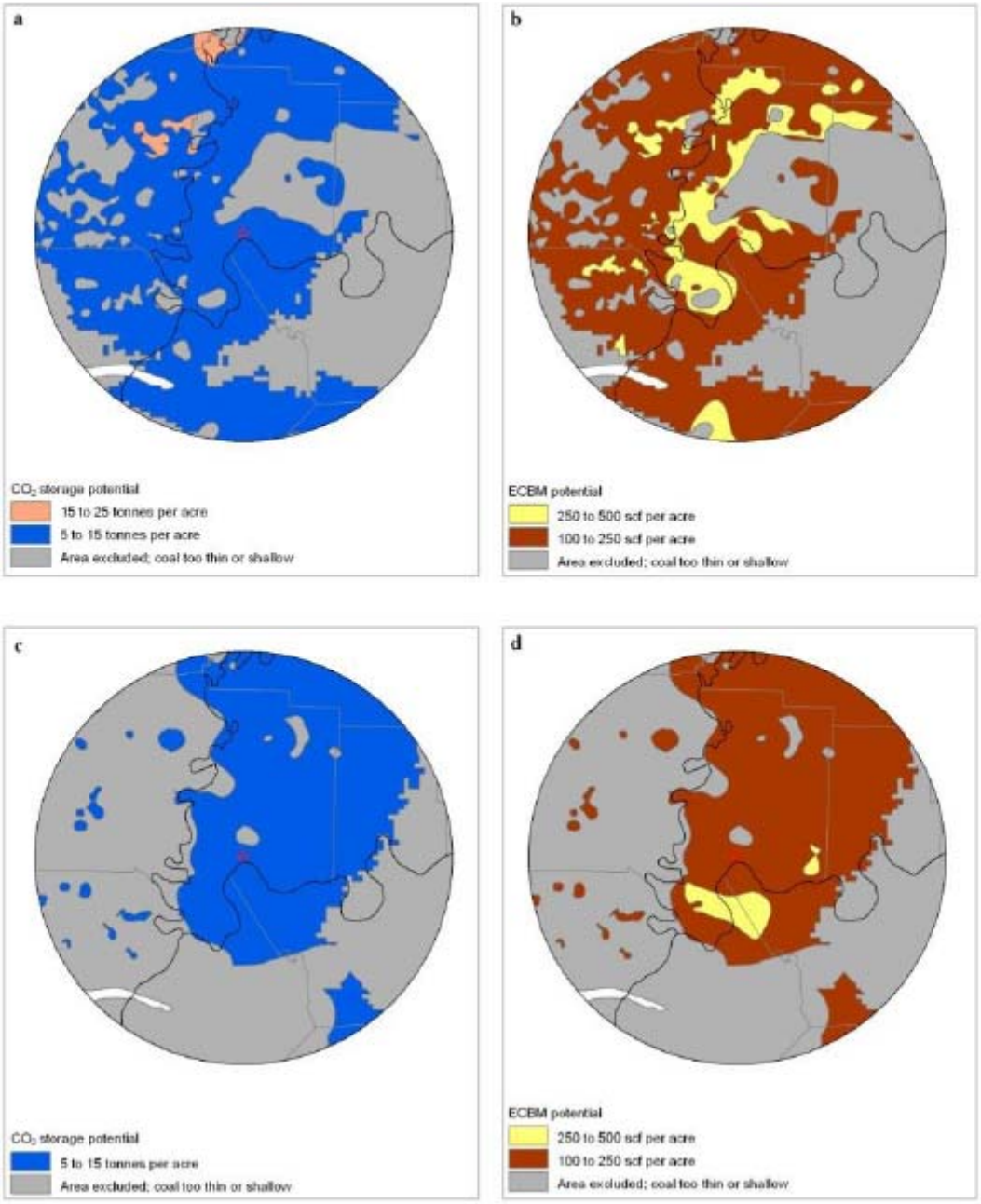


Figure E.4.3. a) & b), CO_2 sequestration and ECBM potentials of the Survant Coal; c) & d), CO_2 sequestration and ECBM potentials of the Colchester Coal in Mt. Vernon

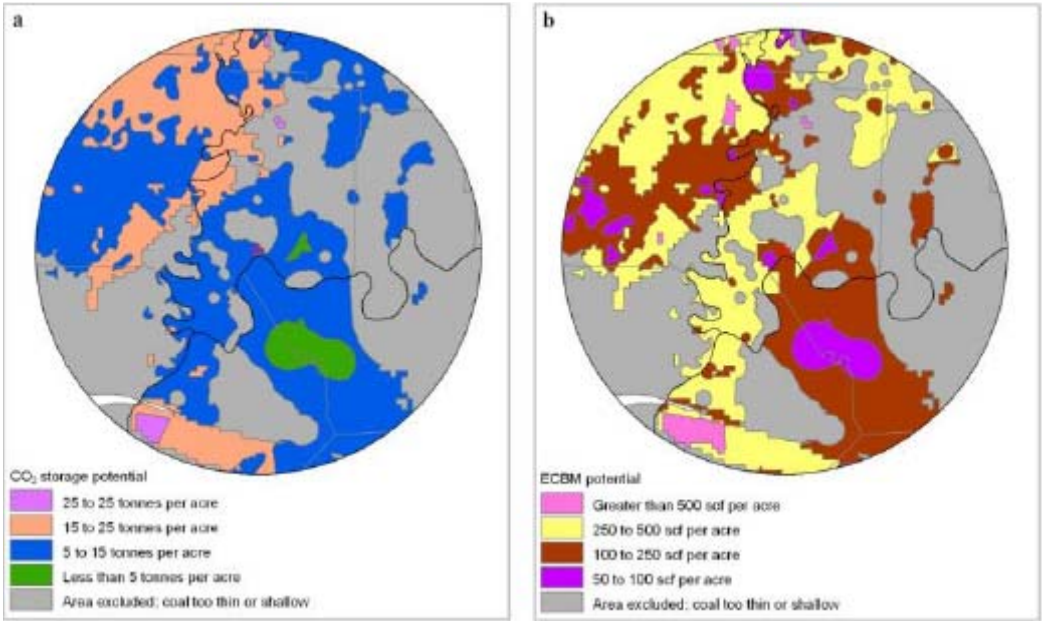


Figure E.4.4. a) & b) CO_2 sequestration and ECBM potentials of the Seelyville Coal in Mt. Vernon

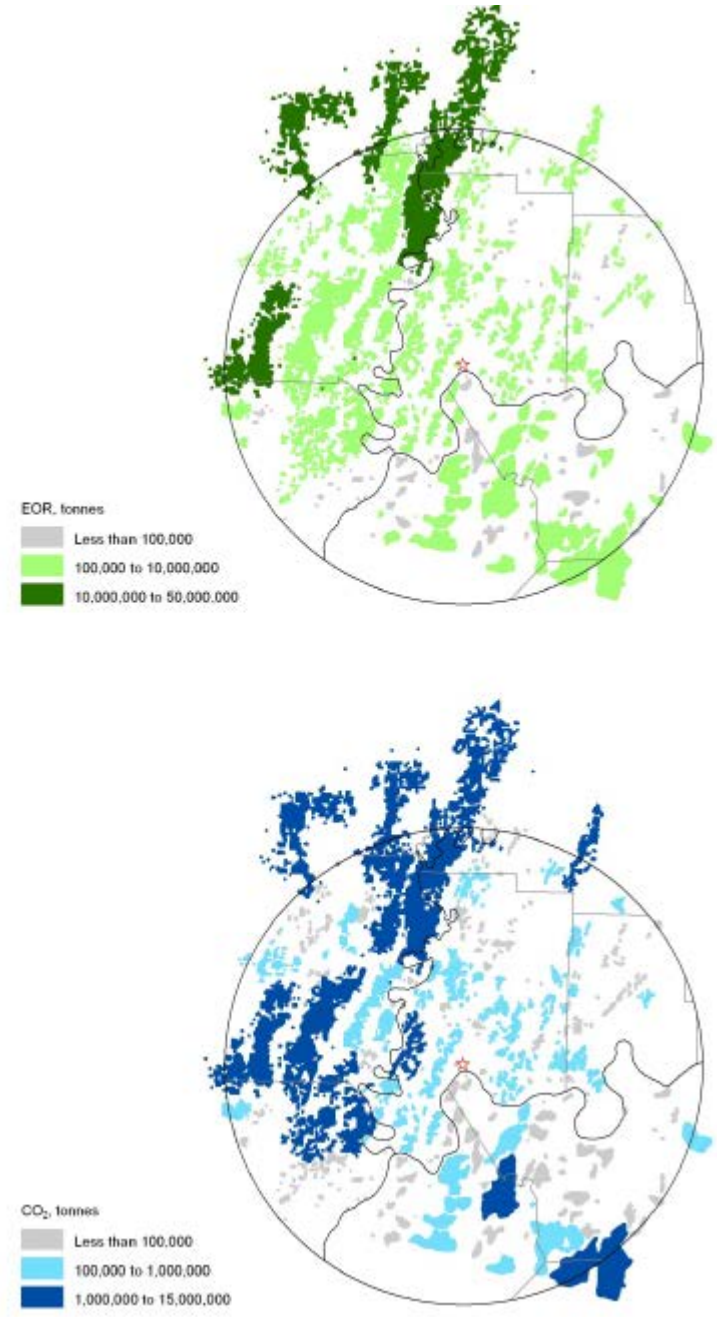


Figure E.4.5. EOR and sequestration potential in the Mt. Vernon area

E.4.3. Sequestration potential in the New Albany Shale and enhanced gas recovery (EGR)

The New Albany Shale, an organic-rich gas shale, underlies all of southwestern Indiana, including the Mt. Vernon buffer zone. The potential for this unit to serve as a reservoir for injected CO_2 as well as for producing gas is described in the following figures. The New Albany Shale is a proven producer of natural gas (shale gas or SG) in Indiana. There exists the potential for enhanced shale gas recovery (EGR). These potentials are shown in Figure E.4.6. Altogether, about 3,731,302,684 scf of shale gas could potentially be recovered with the flooding of about 1,423,666,101 metric tons of CO_2. The depth and thickness of the shale gas deposits in the area are shown in Figure E.4.7.

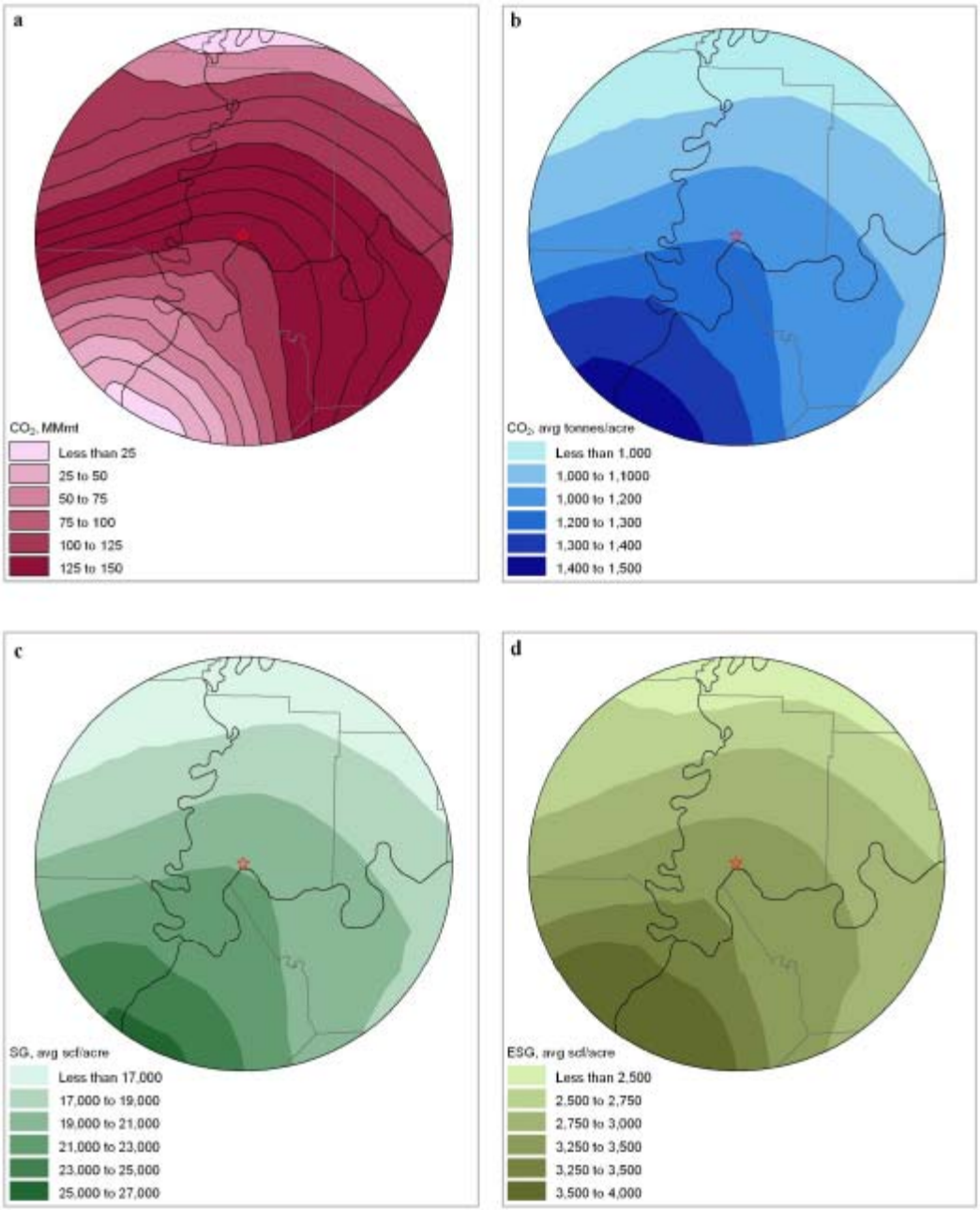


Figure E.4.6. EGR and related CO_2 sequestration potentials in Mt. Vernon area

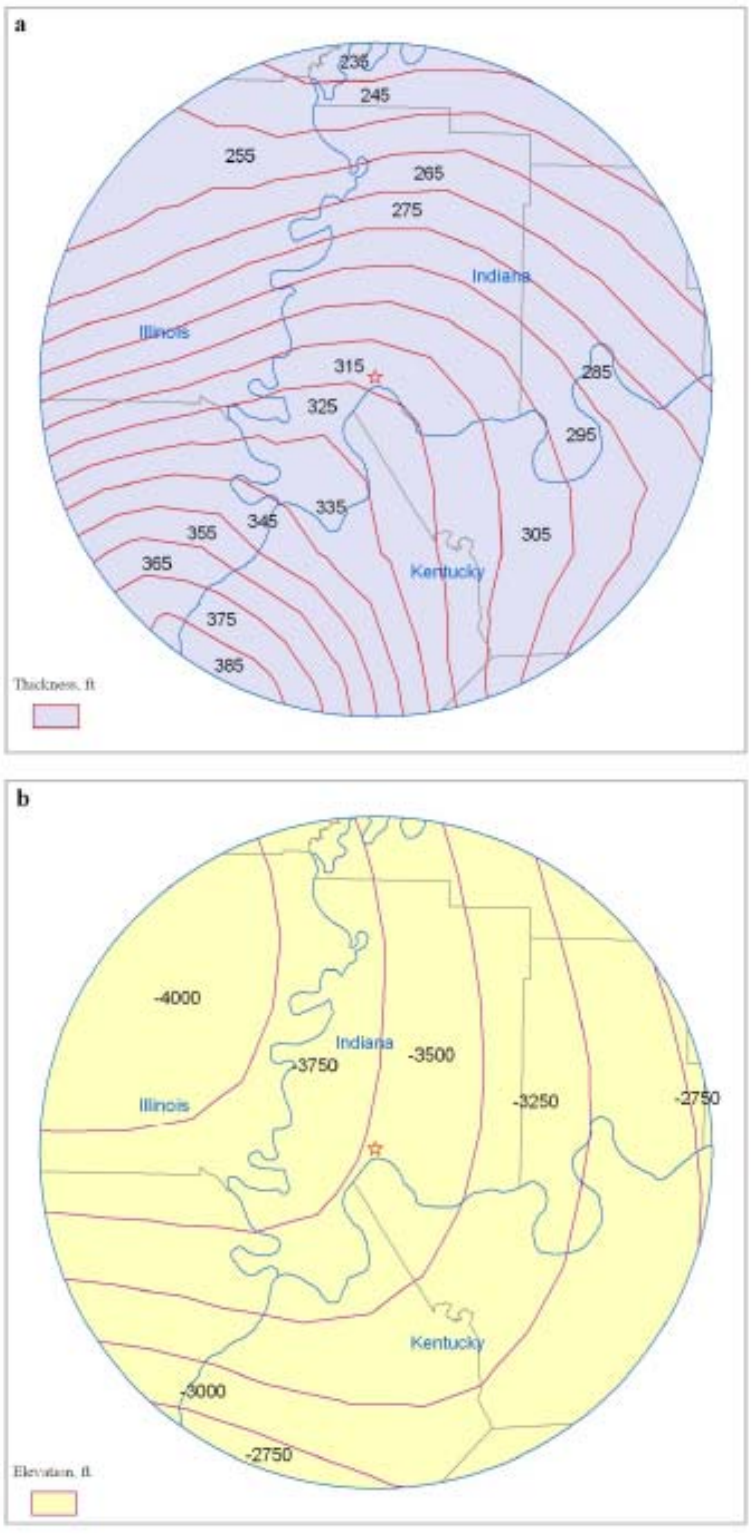


Figure E.4.7. a) Thickness, b) subsea elevation of the New Albany Shale in the Mt. Vernon area

E.4.4. Sequestration potential in saline water-filled aquifers

The potential to use a deep saline water-filled aquifer as a reservoir for injected CO_2 also exists within the Mt. Vernon buffer zone. The results are shown in Figure E.4.8. The map on the left side of the illustration shows the sequestration potential of the unit by displacement of the saline water by injecting CO_2 into the aquifer, while the right side of the diagram represents the sequestration potential by dissolution into saline fluids in the same formation. The CO_2 sequestration potential is about 375,401,616 tons.

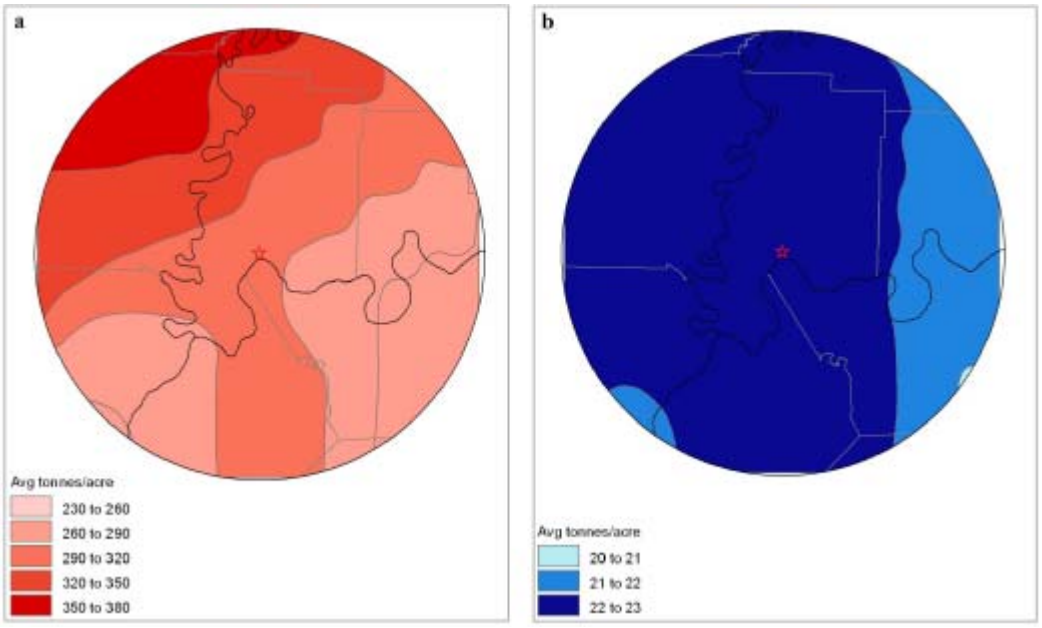


Figure E.4.8. a) Displacement sequestration potential in the Knox Aquifer, b) dissolution sequestration potential in the same formation in Mt. Vernon

E.5. CO_2 sequestration potential in the Minnehaha mining area

E.5.1. ECBM

The coal seams that lie within the area in Indiana surrounding the Minnehaha site are too shallow to be effectively utilized for sequestration of CO_2 within 10 miles of the area for all coal seams as indicated in Figures E.4.1-E.4.3. The only potential for ECBM and ECBM related CO_2 for sequestration is in the extreme western portion of the buffer zone, and primarily in the Survant, Colchester, and Seelyville coal seams. The potential is summarized in Table E.4.1, with a total of 132,085,809 scf of ECBM, and a total of 5,815,027 metric tons of CO_2 storage potential.

Table E.5.1. Sequestration potential in coal seams and ECBM production

Minnehaha	**CO_2 storage potential** *(Metric tons)*	**ECBM recovery potential** *(Standard cubic feet (scf))*
Springfield	2,034,915	46,222,210
Seelyville	8,930,528	202,853,070
Colchester	5,144,243	116,849,239
Danville	3,511,551	79,763,356
Hymera	1,339,680	30,430,248
Herrin	1,533,796	34,839,505
Survant	7,576,486	172,096,596
Totals	30,071,200	683,054,225

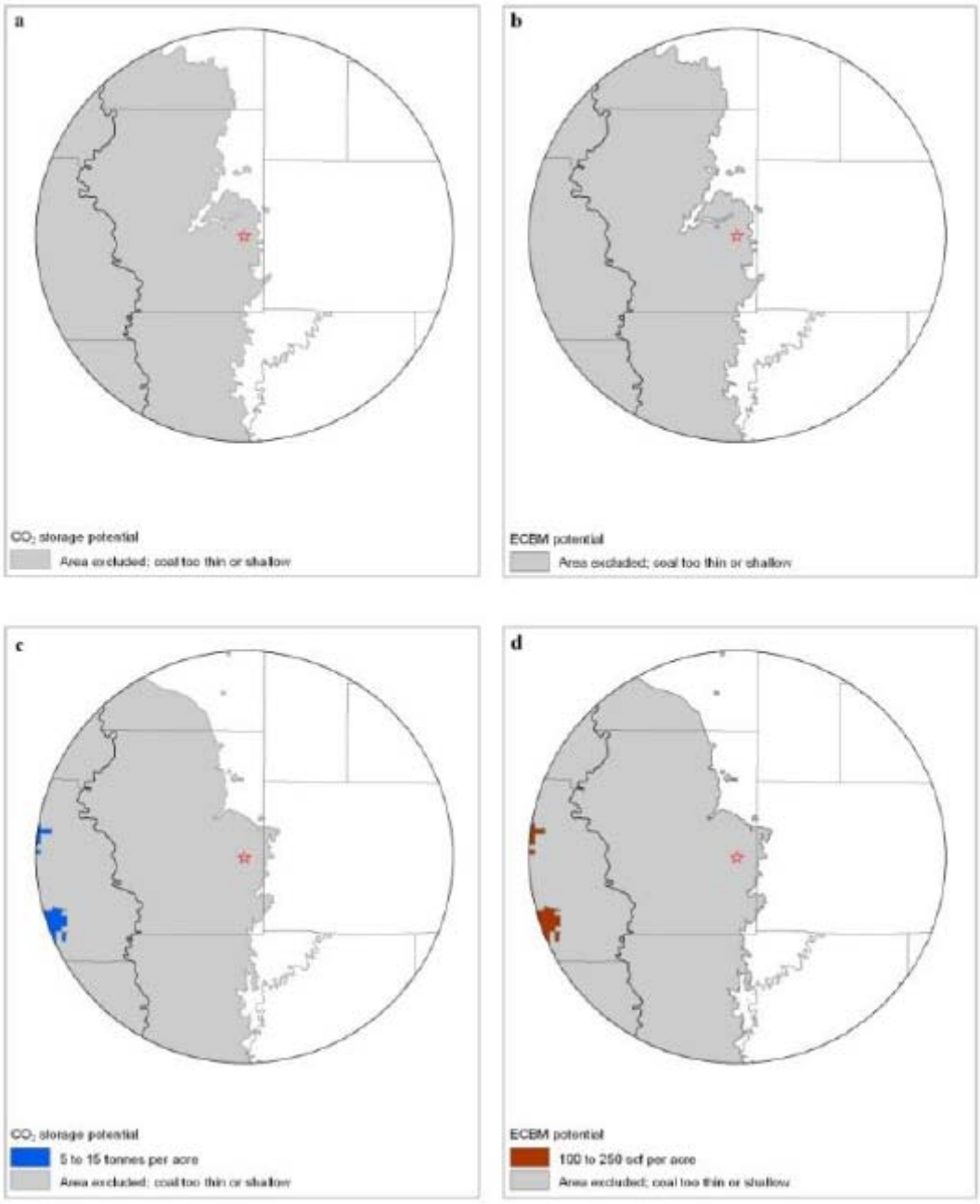


Figure E.5.1. a) & b), CO_2 sequestration and ECBM potentials of the Danville Coal; c) & d), CO_2 sequestration and ECBM potentials of the Hymera Coal in Minnehaha

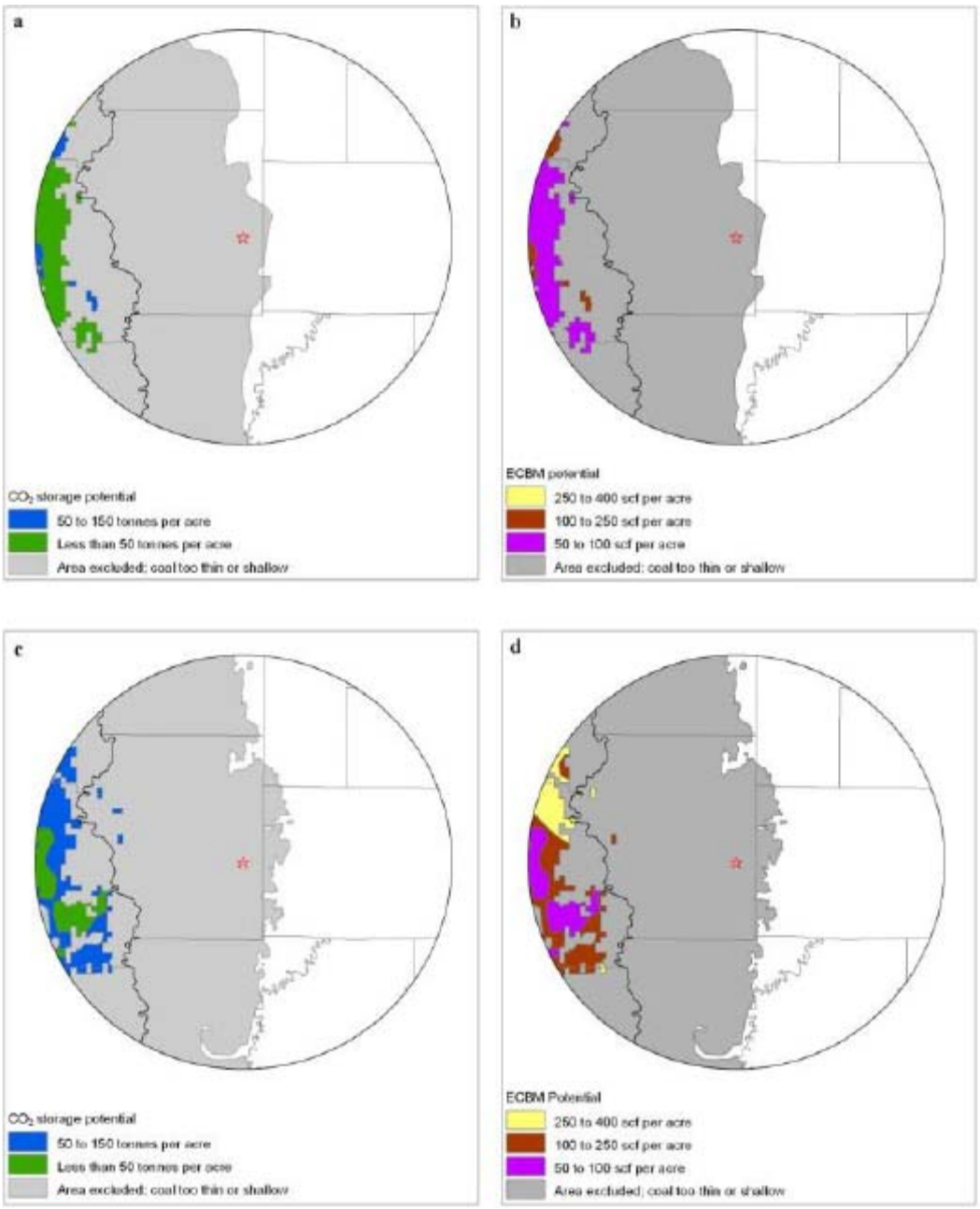


Figure E.5.2. a) & b), CO_2 sequestration and ECBM potentials of the Herrin Coal; c) & d), CO_2 sequestration and ECBM potentials of the Springfield Coal in Minnehaha

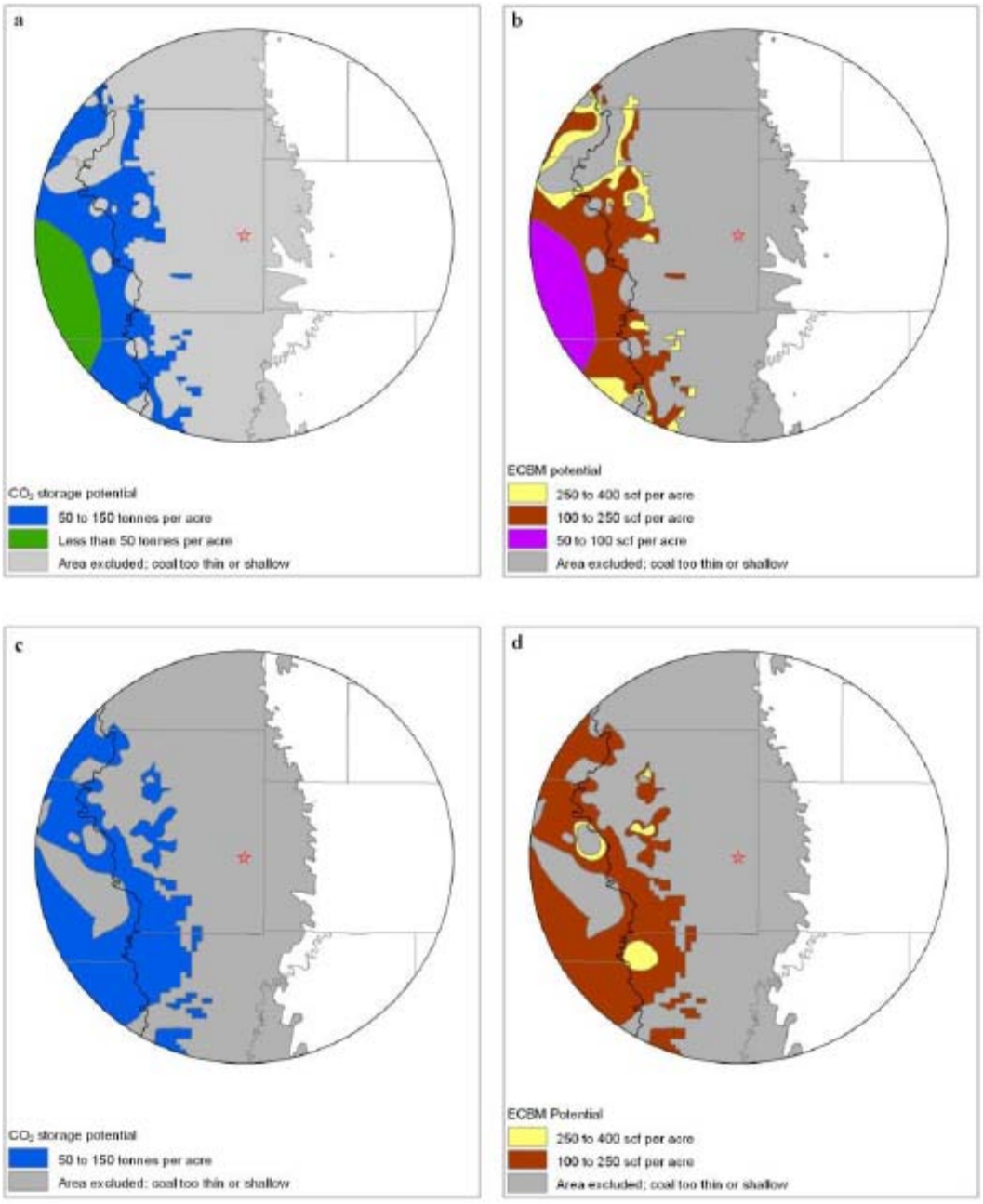


Figure E.5.3. a) & b), CO_2 sequestration and ECBM potentials of the Survant Coal; c) & d), CO_2 sequestration and ECBM potentials of the Colchester Coal in Minnehaha

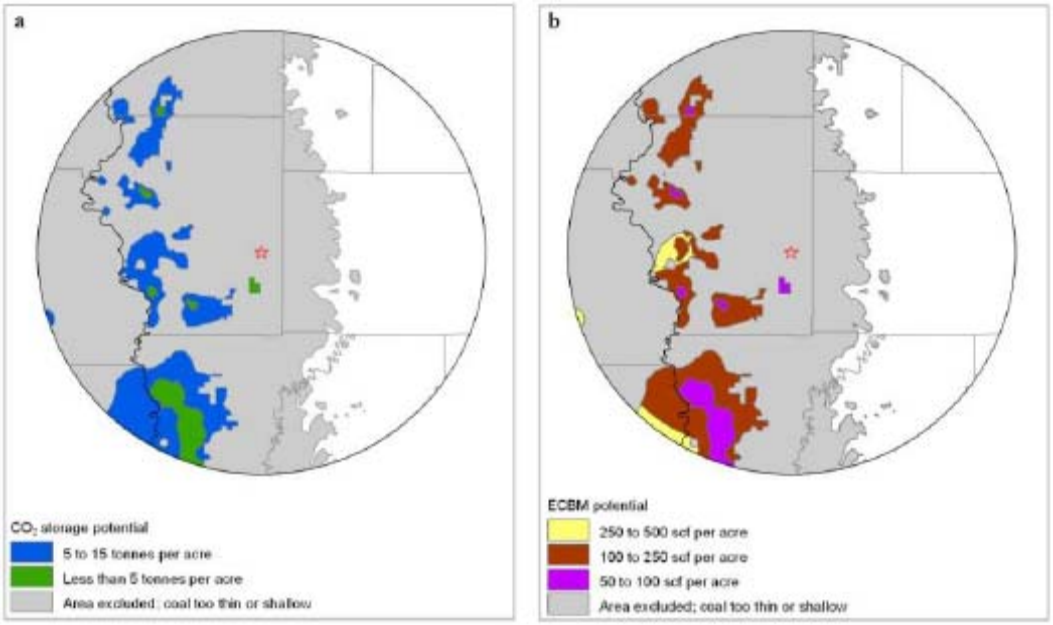


Figure E.5.4. a) & b) CO_2 sequestration and ECBM potentials of the Seelyville Coal in Minnehaha

E.5.2. Sequestration potential in mature oil and gas fields and enhanced oil recovery (EOR)

The potential for using mature oil and gas fields located in the Minnehaha area is shown in Figure E.5.5. Figure E.5.5 shows a general picture of EOR potential around the area, with very few mature oil and gas fields indicated in green. The total potential for EOR and related sequestration are 91,042,106 stb and 17,159,505 tons of CO_2, respectively.

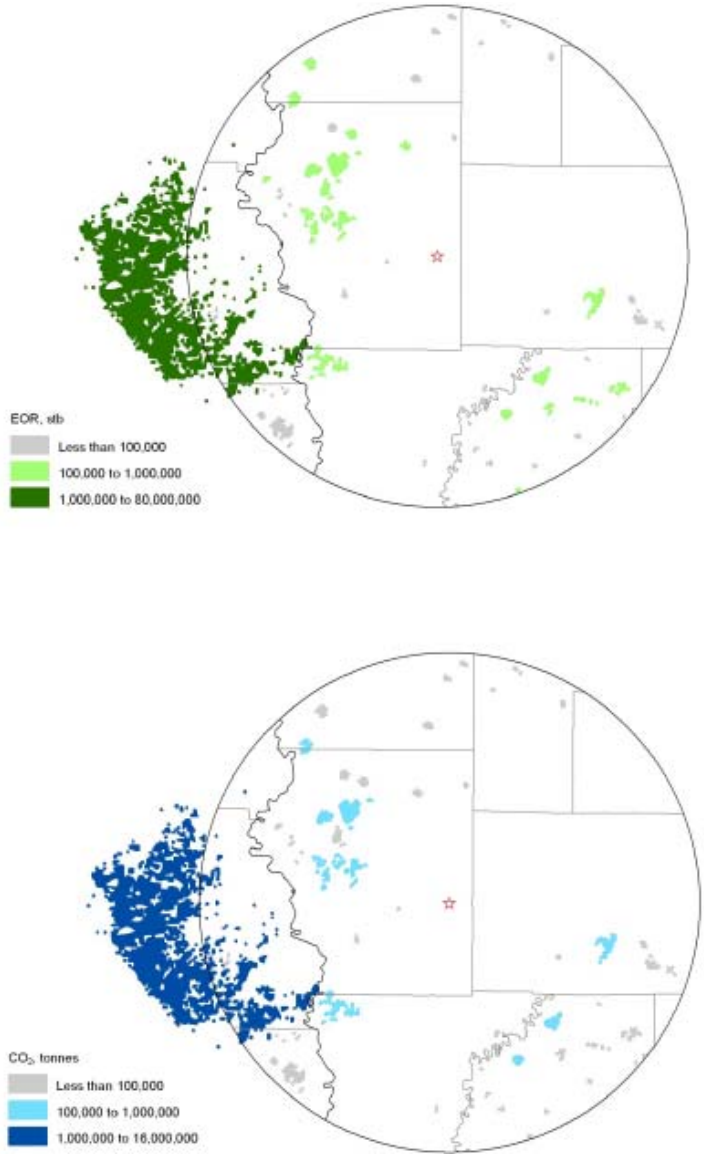


Figure E.5.5. CO_2 sequestration and EOR potentials in Minnehaha

E.5.3. EGR

The New Albany Shale, an organic-rich gas shale, underlies all of southwestern Indiana, including the Minnehaha buffer zone. The potential for this unit to serve as a reservoir for injected CO_2 as well as producing gas is described in the following figures. The New Albany Shale is a proven producer of natural gas (shale gas or SG) in Indiana. There exists the potential for enhanced gas recovery (EGR) production. These potentials are shown in Figure E.5.6. Altogether, about 1,526,155,741 scf of shale gas could potentially be recovered with the flooding of about 582,299,636 metric tons of CO_2. The depth and thickness of the shale gas deposits in the area are shown in Figure E.5.7.

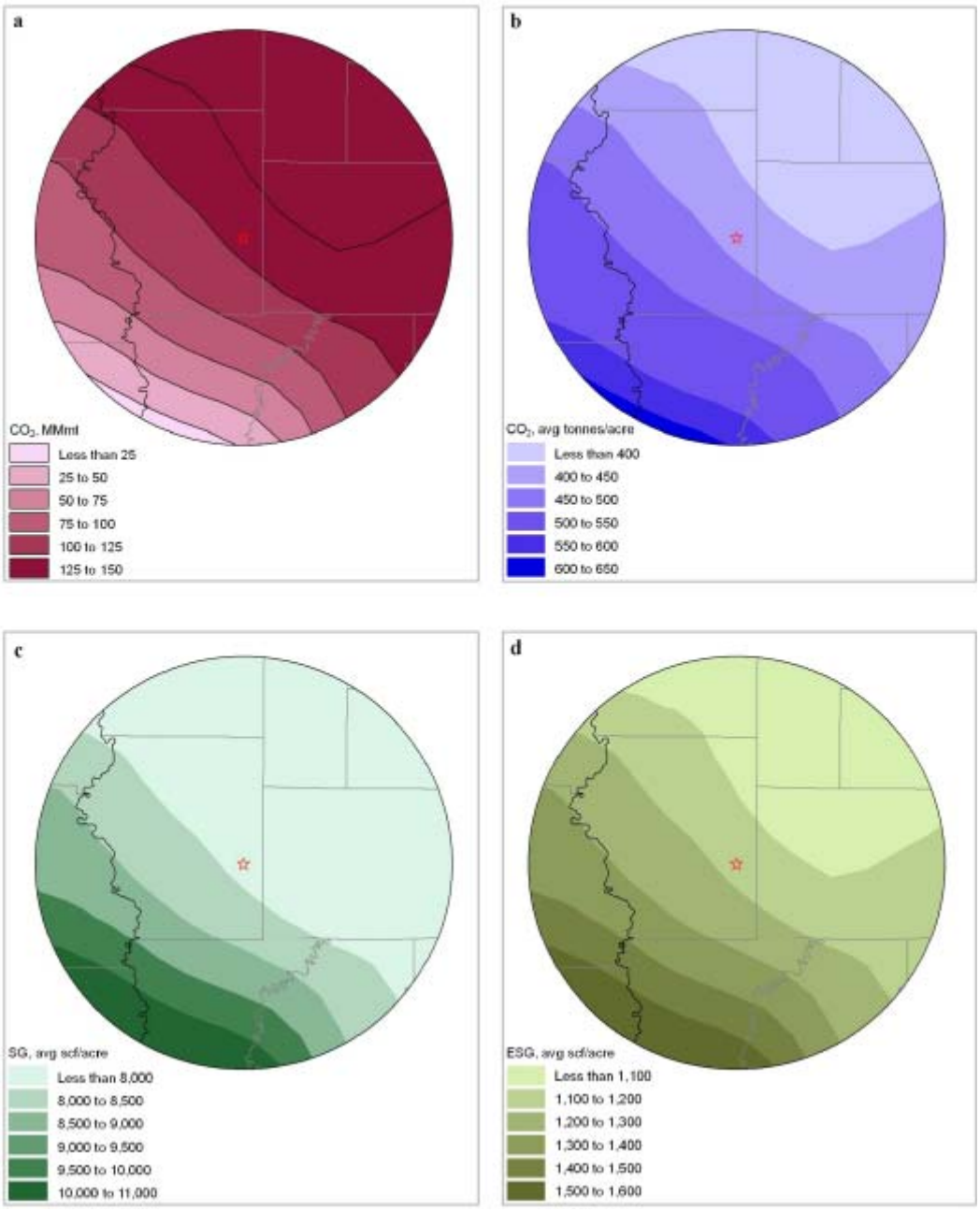


Figure E.5.6. a) CO_2 sequestration in million tonnes in the area: b) average tons/acre; c) SG scf/acre, d) EGR per acre

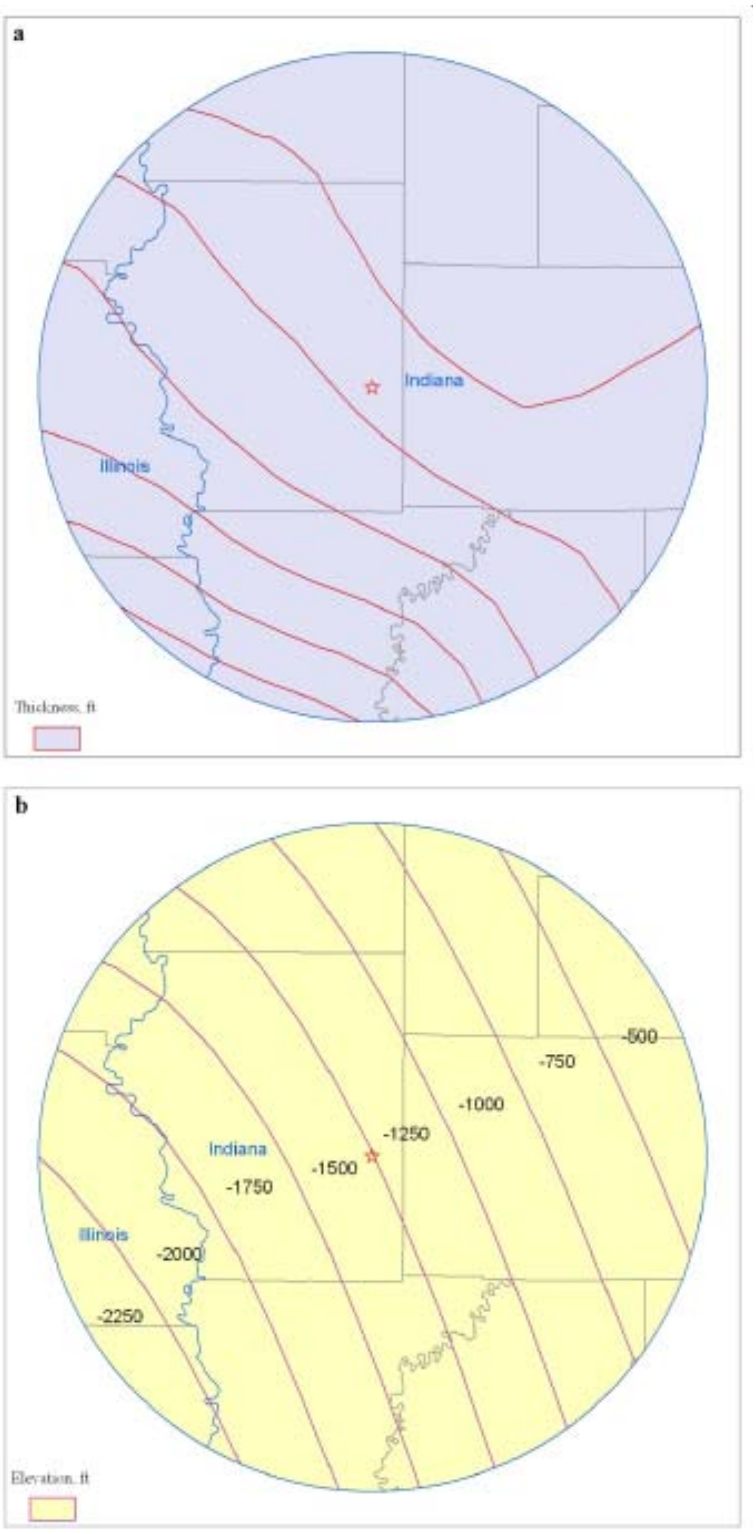


Figure E.5.7. a) Thickness, b) subsea elevation of the New Albany shale in the Minnehaha and NSA Crane area, Sullivan County

E.5.4. Sequestration potential in saline water-filled aquifers

The potential to use a deep saline water-filled aquifer as a reservoir for injected CO_2 also exists within the Minnehaha buffer zone. The results are shown in Figure E.5.8, where the left circle shows the sequestration potential in the Mt. Simon Aquifer, and right circle represents the sequestration potential in the St. Peter Aquifer. The CO_2 sequestration potential is about 15,365,160,702 metric tons in the Mt. Simon Aquifer and about 475,923,991 metric tons in the St. Peter Aquifer.

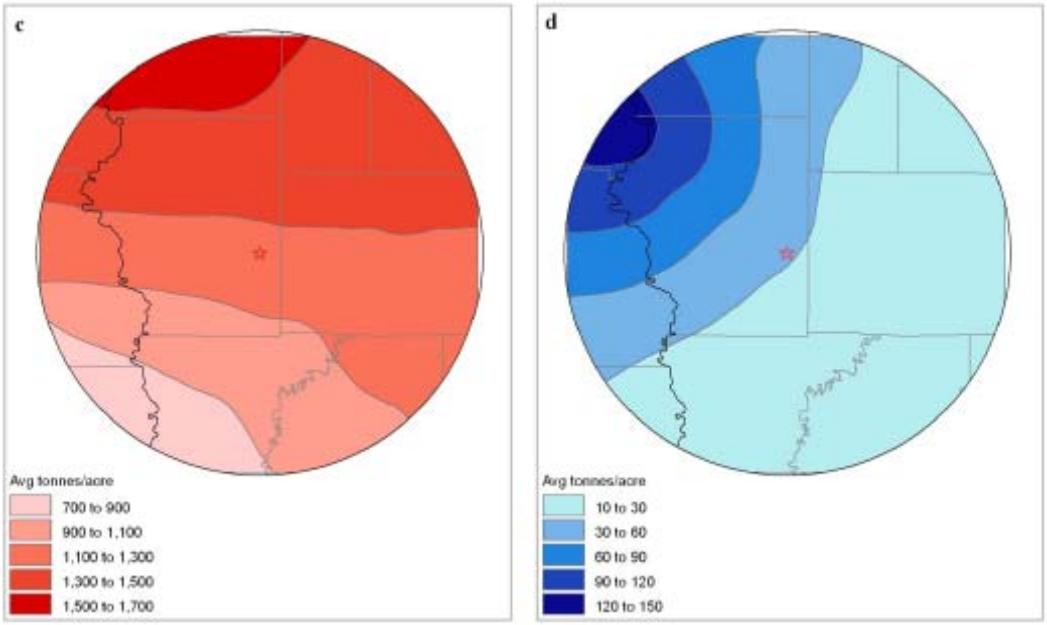


Figure E.5.8. c) CO_2 sequestration potential in Mt. Simon Aquifer, d) in St. Peter Aquifer

E.6. Summary

Table E.6.1 summarizes the calculated sequestration potential in saline aquifers, oil wells, shale deposits, and coal beds, as well as estimated enhanced oil recovery, shale gas production and enhanced shale gas production for each of the four regions: Francisco, Merom, Minnehaha, and Mt. Vernon. While additional work is needed to refine these numbers, they give a rough idea of the potential at the alternative sites.

Table E.6.1. Summary of sequestration potential for Francisco, Merom, Minnehaha, and Mt. Vernon

	Francisco	**Merom**	**Minnehaha**	**Mt. Vernon**
CO_2 Sequestration Potential (tons)	47,923,701	27,983,570	17,159,505	75,612,238
EOR (stb)	212,352,317	157,733,088	91,042,106	275,400,729
CO_2 Sequestration Potential (tons)	1,001,956,031	618,883,538	582,299,636	1,423,666,101
Enhanced Shale Gas (tons)	17,506,919,752	10,813,592,707	10,174,371,605	24,875,351,224
Shale Gas (scf)	2,626,037,963	1,622,038,906	1,526,155,741	3,731,302,684
Saline Aquifer Displacement Mt. Simon (tons)	15,103,902,176	15,365,160,702	n/a	n/a
Saline Aquifer Displacement St. Peter (tons)	764,995,646	475,923,991	n/a	n/a
Saline Aquifer Displacement Knox (tons)	n/a	n/a	375,401,616	371,604,241
Saline Aquifer Dissolution Mt. Simon (tons)	908,551,593	896,260,716	n/a	n/a
Saline Aquifer Dissolution St. Peter (tons)	81,297,233	51,911,093	n/a	n/a
Saline Aquifer Dissolution Knox (tons)	n/a	n/a	28,220,835	42,613,925
Saline Aquifer Combined Storage Mt. Simon (tons)	16,012,453,769	16,261,421,418	n/a	n/a
Saline Aquifer Combined Storage St. Peter (tons)	846,292,879	527,835,084	n/a	n/a
Saline Aquifer Combined Storage Knox (tons)	n/a	n/a	403,622,451	414,218,166