GIS Analysis of the Distribution and Estimated CO_2 Storage Volume of the Devonian Shale

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Note: Grid data sets are indicated in matrix notation using the courier type face, i.e., [`grid_data`]

Carbon sequestration capacity in million tons per square kilometer was calculated from a grid that contains shale thickness (isopach) data for those areas in the Illinois and Appalachian Basins of Illinois, Indiana, Kentucky, and Ohio where the shale is 100 feet or greater in thickness and 1,000 feet or deeper below the ground surface. Two basic assumptions were employed in the calculations and uniformly applied to the entire gridded area. The adsorbed gas content of the shale is 40 scfCO_2/ton (short ton) and shale density is 2.6 g/cc. These assumptions yield a conversion factor of 2024.3 for use in converting thickness in feet per 1-kilometer square grid cell to short tons of CO_2. Thus million metric tonnes of CO_2 per grid cell was calculated with the formula:

[`devsh_dpthk`] *(2024.3*0.907185).AsGrid

where 1 short ton (2000 lbs) = 0.907185 metric tonnes

For the multi-state analysis, a grid of drilling depth to the top of the shale was required for deriving the [`devsh_dpthk`] grid. This was accomplished by obtaining 90-meter resolution Shuttle Radar Topography Mission (SRTM) data for the multi-state area from the U.S. Geological Survey (http://seamless.usgs.gov). These data were resampled to a 1-kilometer grid spacing. The top of shale structure grid was then subtracted from the resulting surface elevation grid to yield a gridded estimate of drilling depths.

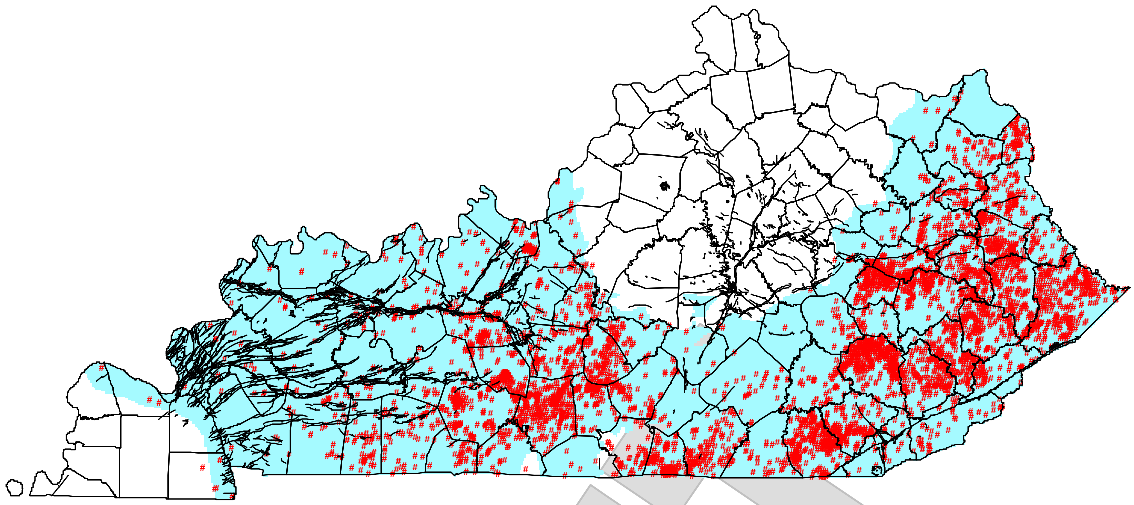
This grid-based method was developed from an initial analysis of the sequestration capacity of the Ohio and New Albany (Devonian) shales in Kentucky. Geographic information system (GIS) software was used to perform an analysis of the thickness and distribution of the Devonian black shale in Kentucky. The initial goal is to calculate the number of tons of shale in place by county for those areas with drilling depths to the shale of at least 1,000 feet and a shale thickness of at least 50 feet (note 100 feet or greater was selected for the final multi-state analysis). These cutoffs were selected to ensure reservoir integrity (deeper than the expected depth of surface fracturing) and gas reservoir potential. With the number of tons of shale being determined, a series of factors to calculate the sequestration potential in tons of CO_2 are derived based on measured CO_2 storage capacity and shale density. For GIS, ESRI's ArcView 3.2 and Spatial Analyst were used. The Kentucky Geological Survey uses a server running

SQL-2000 for data storage. Data are accessed with tables linked to a graphic user interface implemented using Microsoft Access 97. Access queries were composed to compile point data sets consisting of the locations and values of Devonian shale stratigraphic tops and thickness. The formation tops data were maintained as drilling depth to the top of the formation rather than elevations with respect to sea level. Open database connectivity (ODBC) services are available from ArcView. The Access query results were added to the GIS as tables using the SQL Connect facility and then converted to shape files.

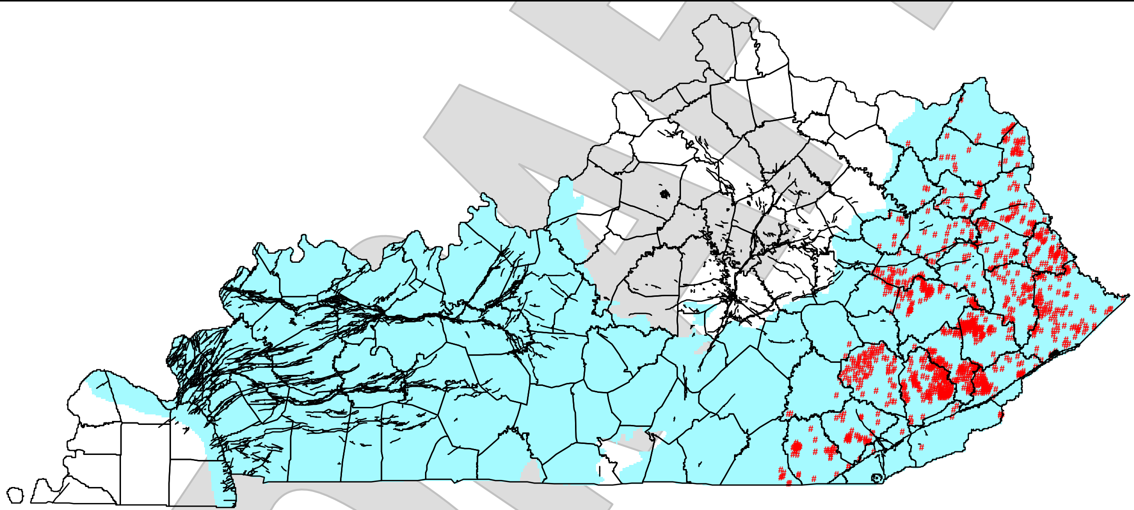
```
SELECT dbo_well_identification.record_number AS recno,
dbo_geographic_location.north_latitude AS lat,
dbo_geographic_location.west_longitude AS lon, dbo_formation_tops.pick_fm,
dbo_geographic_location.surface_elevation AS elev, dbo_formation_tops.fm_top,
dbo_formation_tops.fm_base, [fm_base]-[fm_top] AS thick
FROM ((dbo_geographic_location INNER JOIN dbo_geographic_region ON
dbo_geographic_location.location_index =
dbo_geographic_region.location_index) INNER JOIN dbo_well_identification ON
dbo_geographic_location.location_index =
dbo_well_identification.location_index) INNER JOIN dbo_formation_tops ON
dbo_well_identification.record_number = dbo_formation_tops.record_number
WHERE (((dbo_formation_tops.pick_fm)="341OHIO" Or
(dbo_formation_tops.pick_fm)="341CHAT" Or
(dbo_formation_tops.pick_fm)="341NALB") AND ((dbo_formation_tops.fm_top) Is
Not Null) AND ((dbo_formation_tops.fm_base) Is Not Null) AND (([fm_base]-
[fm_top])>0) AND ((dbo_formation_tops.type_of_top)="s") AND
((dbo_geographic_location.ns_feet)>0) AND ((dbo_geographic_location.n_or_s)
Is Not Null) AND ((dbo_geographic_location.ew_feet)>0) AND
((dbo_geographic_location.e_or_w) Is Not Null) AND
((dbo_geographic_location.carter_section)>0) AND
((dbo_geographic_location.carter_letter)>=" A") AND
((dbo_geographic_location.carter_number) Is Not Null));
```

Sample SQL query composed with the Access GUI for compiling Devonian shale stratigraphic and location point data.

Existing polygon shape files of the Kentucky counties, faults, and the subsurface distribution of the Devonian shale in Kentucky (`[Subsurf]`) were employed in the analysis. The shape file of the subsurface distribution of the shale was converted to a grid for use in the spatial analysis. Each cell of this grid contained a value of 1 (true) if the shale existed in the subsurface over the area of the cell. All other cells were set to null, the no data value. All grids were computed with 1,000-meter (1 kilometer) cell dimensions. Analyses were performed using the North American Datum of 1927 (NAD27) with the projection set to UTM zone 16.



Subsurface distribution of the Devonian shale (blue, shaded) with stratigraphic data points.



Subsurface distribution of the Devonian shale (blue, shaded) with stratigraphic data points for the Lower Huron Member of the shale.

For deriving drilling depth and thickness maps, grids were interpolated from point data using the inverse distance weighted (IDW) nearest neighbor method. The interpolated data were processed to establish which grid cells fit the selection criteria of 1,000 feet or deeper drilling depths and a shale thickness of at least 50 feet.

```
Interpolate grid, [Depth], using drilling depth from point file
Interpolate grid, [Iso], using thickness data from point file
Map Query [Depth]>=1000 = [Deep]
Map Query [Iso]>=50 = [Thick]
Calculate [Deep]*[Thick] = [Temp01]
Calculate [Temp01]*[Subsurf] = [Temp02]
([Temp02] = 0.AsGrid).SetNull([Temp02]) = [DeepThick]
```

Method for deriving a grid dataset indicating the distribution of shale at least 50 feet thick and 1,000 feet deep.

To restrict the volume calculations to the limits of the distribution of thicker and deeper shale, the `[Iso]` and `[DeepThick]` grid data sets were multiplied together to produce a new grid, `[Target]`.

To limit the number of calculation steps required to derive volume and sequestration potential estimates, conversion factors were derived to convert the thickness (isopach in feet) data in `[Target]` to million tons of shale and then directly to CO2 tons. Tons of shale in place is a function of shale volume and density, thus:

$$Tons_{shale} = volume * density$$

and

$$MMTons_{shale} = \frac{thickness * area * density}{1000000}$$

Assuming thickness in feet, a1 kilometer cell size, a density in *g/cc* million tons of shale in place can be calculated:

$$MMTons_{shale} = \frac{thickness * \frac{0.3048\,m}{ft} * (1000\,m)^2 * density * 1.102}{1000000} \qquad \text{Eq. 1.}$$

where:	*thickness*	= thickness of shale in feet
	1000	= cell size in meters
	density	= bulk density from compensated density log
	1.102	= density conversion factor to convert from grams per cubic centimeter to tons per cubic meter

For a specified density, the constants in equation 1 can be combined to obtain a direct conversion factor that is a function only of shale thickness. Substituting different shale densities, a factor, `CfMMTons`, would be one of:

2.5 g/cc (log estimated density for Lower Huron)	= 0.840
2.6 g/cc (log estimated density for upper part of shale)	= 0.873
2.65 g/cc (log handbook typical shale density)	= 0.890

To calculate million tons of shale per cell, the ArcView grid calculation would be:

```
[Target]*CfMMTons.AsGrid = [MMTons]
```

Different conversion factors could be derived for standard reservoir analysis (as opposed to assuming adsorbed gas). Distributions of porosity, water or oil saturation data, and others could be gridded and used to derive oil or gas in place estimates.

Converting tons of shale in place to estimated tons of CO_2 sequestered requires an additional factor based on the gas content per ton of shale from CO_2 adsorption data. Using a gas content of 1 standard cubic foot of CO_2 per ton and 17.25[1] thousand cubic feet (Mcf) CO_2 per ton of CO_2, there will be 57.97 tons of CO_2 per million tons of shale.

$$TonsCO_2 = \frac{ft^3_{CO_2}}{ton_{shale}} * 1000000 * \frac{Mcf}{1000\, ft^3_{CO_2}} * \frac{ton_{CO_2}}{17.25 Mcf} = 57.97 \qquad \text{Eq. 2}$$

The sequestration volume in tons of CO_2 can now be considered a function of thickness, shale density, and adsorbed gas content, or:

$$TonsCO_2 = 57.97 * CfMMTons * thickness * gascontent$$

Multiplying the 57.97 and *CfMMTons* provides a single factor that varies only with density:

Factor = 48.69 at density equals 2.5 g/cc
Factor = 50.61 at density equals 2.6 g/cc
Factor = 51.59 at density equals 2.65 g/cc

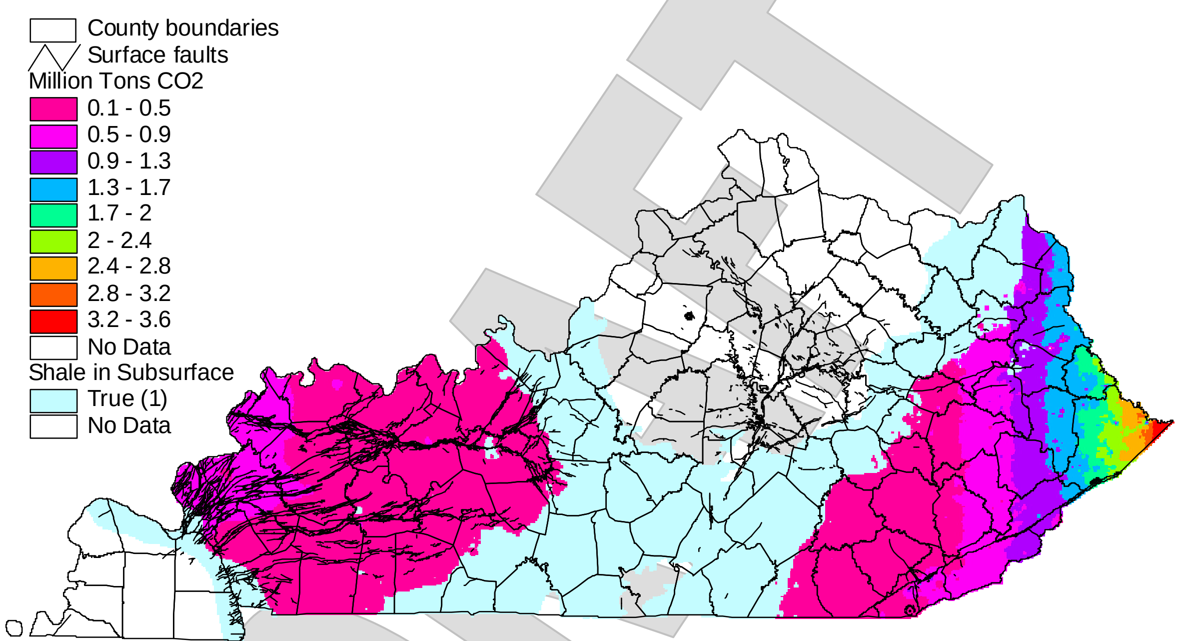
In lieu of gridding gas content data, multiplying a measured gas content by one of these factors yields a final selection of factors for use in converting shale thickness data directly to tons of CO_2 sequestered. For example, using a gas content of 40 scf/ton, a shale density of 2.6 g/cc, and a 1000-meter cell size, the tons of CO_2 per cell is 2024.3 per foot of shale thickness, thus:

```
[Target] * (2024.3).AsGrid = [CO2Tons]
```

[1] 17.25 Mcf CO_2 per ton CO_2 is the conversion factor used by the U.S. EPA. Conversion is derived from gas laws and is valid for 60°F and 1 atmosphere pressure.

As additional gas content data are acquired, examining the distribution and gridding the data as appropriate will be used to refine the sequestration volume calculations.

The values calculated for each cell require summation for specific regions to obtain totals. With the county polygon theme active, the ArcView Summarize Zones procedure (available from the Analysis menu command) was used to summarize the data by county. The field defining the zones was the county name and the `[CO2Tons]` grid theme was selected for summarizing. A table of summary statistics was computed that could be joined to the original county table for mapping and additional analysis.



CO2 storage capacity per square kilometer in million tons.

Summary table of potential sequestration totals million short tons of CO_2 by county (gas content 40 scf/ton, shale density 2.6 g/cc, cell size 1,000 meters):

Name	Basin	Count	Min	Max	Mean	MMTonsCO2
BELL	160	949	0.24	1.52	0.51	486.8
BOYD	160	420	1.03	1.70	1.39	583.9
BREATHITT	160	1293	0.38	1.05	0.60	775.2
CARTER	160	329	0.34	1.26	1.05	346.6
CLAY	160	1236	0.24	0.48	0.35	433.2
ELLIOTT	160	292	0.29	1.14	0.92	267.2
FLOYD	160	1040	0.27	1.79	1.42	1,474.4
GREENUP	160	339	0.99	1.38	1.24	421.7
HARLAN	160	1211	0.31	1.17	0.76	918.6
JACKSON	160	275	0.21	0.34	0.25	69.4
JOHNSON	160	657	0.86	1.67	1.28	839.8
KNOTT	160	918	0.78	1.42	1.06	969.9
KNOX	160	1017	0.20	0.47	0.31	318.5

Name	Basin	Count	Min	Max	Mean	MMTonsCO2
LAUREL	160	1146	0.16	0.38	0.22	255.7
LAWRENCE	160	1089	0.20	1.85	1.37	1,490.6
LEE	160	232	0.22	0.50	0.35	81.6
LESLIE	160	1066	0.38	0.79	0.55	590.8
LETCHER	160	894	0.21	1.70	1.13	1,012.2
MAGOFFIN	160	793	0.63	1.20	0.92	730.8
MARTIN	160	631	1.23	2.32	1.76	1,113.1
MCCREARY	160	703	0.10	0.24	0.15	107.8
MENIFEE	160	16	0.37	0.42	0.39	6.2
MORGAN	160	710	0.25	1.19	0.70	496.8
OWSLEY	160	497	0.13	0.44	0.34	168.0
PERRY	160	892	0.37	1.04	0.71	630.4
PIKE	160	2056	0.82	3.60	2.17	4,467.3
POWELL	160	7	0.31	0.34	0.32	2.2
ROCKCASTLE	160	4	0.19	0.21	0.20	0.8
ROWAN	160	2	0.54	0.54	0.54	1.1
WHITLEY	160	1161	0.16	0.70	0.22	261.1
WOLFE	160	525	0.20	0.81	0.45	237.1
Appalachian	**160 Total**					**19,558.9**
MARSHALL	250	29	0.39	0.56	0.48	13.9
Jackson Purchase	**250 Total**					**13.9**
EDMONSON	300	670	0.12	0.40	0.24	157.5
HARDIN	300	220	0.13	0.18	0.16	35.3
HART	300	178	0.11	0.20	0.15	26.4
MEADE	300	106	0.18	0.22	0.20	21.6
PULASKI	300	58	0.14	0.18	0.16	9.3
WARREN	300	424	0.12	0.38	0.20	84.0
Cincinnati Arch	**300 Total**					**334.2**
BRECKINRIDGE	315	1426	0.10	0.26	0.19	274.8
BUTLER	315	1130	0.11	0.41	0.28	320.3
CALDWELL	315	898	0.27	0.67	0.48	430.0
CHRISTIAN	315	1870	0.11	0.58	0.25	470.0
CRITTENDEN	315	968	0.31	0.90	0.66	634.1
DAVIESS	315	1255	0.12	0.46	0.32	404.1
GRAYSON	315	1277	0.12	0.49	0.27	343.6
HANCOCK	315	516	0.15	0.54	0.29	150.5
HENDERSON	315	1233	0.11	0.64	0.45	560.8
HOPKINS	315	1464	0.14	0.64	0.41	595.7
LIVINGSTON	315	696	0.42	0.67	0.60	415.6
LOGAN	315	966	0.12	0.25	0.19	183.1
LYON	315	620	0.28	0.59	0.46	284.8
MCLEAN	315	671	0.14	0.56	0.39	259.9
MUHLENBERG	315	1266	0.12	0.59	0.34	425.4
OHIO	315	1549	0.16	1.09	0.37	573.4
TODD	315	879	0.10	0.31	0.18	156.9
TRIGG	315	848	0.16	0.34	0.24	200.6
UNION	315	953	0.57	0.81	0.69	657.7
WEBSTER	315	878	0.17	0.68	0.51	445.1
Illinois Basin	**315 Total**					**7,786.5**
	Grand Total					**27,693.5**
Years sequestration available at 80,000,000 tons CO2 per year						**346.2**

Basin is the USGS/AAPG geologic basin code.
Count is the total number of grid cells within the county boundary.
Min is the minimum observed tons of CO_2 per square kilometer.
Max is the maximum observed tons of CO_2 per square kilometer.
Mean is the minimum observed tons of CO_2 per square kilometer.
MMTonsCO2 is sum of observed tons of CO_2 per square kilometer for all cells within the county boundary. Multiply this number by 0.907185 to convert to million metric tones.

The values shown in this table are provided to illustrate an application of the estimation method described in this appendix. The numbers are subject to revision and do not represent final conclusions of this project. Additional CO_2 adsorption capacity data will be acquired to refine the estimates. Consideration will be given to other adjustments to the total that might include evaluating areas likely to have little or no sequestration potential even though they are mathematically included in the area of deep and thick shale. These areas will be excluded. For example, based on experience in oil and gas field exploration and development, Marshall, Pulaski, and Rockcastle counties are areas of marginal potential that have a relatively small likely-hood of being developed for carbon sequestration.