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REGULAR ARTICLE

Geologic perspective for carbon sequestration by woody biomass burial

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Abstract. Carbon sequestration by Woody Biomass Burial (WBB) leverages carbon capture through natural photosynthesis, followed by the isolation of dead or fallen wood in a relatively shallow Underground Wood Vault (UWV). Long-term geologic containment, including any greenhouse gas decomposition products, depends on the careful selection of UWV location and depth. To achieve carbon sequestration durability of 100 y, an initially low-moisture UWV should be built as follows: (a) low-permeability, high-plasticity clays with a hydraulic conductivity of $\leq 10^{-9}$ m/s, and with vertical/lateral separation distance of ≥ 1 m from the nearest aquifer; (b) residual compaction voids at least partially filled, with loose, smectite-rich clay; (c) capped with ≥ 2 m of clay compacted to achieve hydraulic conductivity $< 5 \times 10^{-9}$ m/s; (d) restricted to locations where the 50-y seismic Peak Ground Acceleration (PGA) is $\leq 9\%$ g (8.8×10^{-1} m/s^2). A UWV built in a low-PGA location, with larger cap and confinement thicknesses and/or lower hydraulic conductivity, should be capable of sequestration durability approaching 500–1000 y or more.

Keywords: Carbon sequestration, Woody biomass burial, Wood harvest sequestration, Wood vault, Carbon storage geology.

1 Introduction

1.1 Carbon sequestration as a response to climate change

Carbon dioxide (CO_2) has been implicated as the principal GreenHouse Gas (GHG) responsible for global warming and the associated effects of climate change [1]. In addition to efforts to reduce anthropogenic GHG emissions, various methods have been proposed to remove excess CO_2 from Earth's atmosphere, with the captured carbon either being converted into immobile forms or isolated (i.e., sequestered) to prevent a return to circulation [2].

Many different methods, designated as Negative Emission Technology (NET), offer prospects for CO_2 Direct Removal (CDR) [3, 4]. However, most of the potential CDR methods involve technology which might be too expensive to be economically sustainable at the scale needed for climate mitigation. Therefore, attention is being paid to alternative low-technology methods which take advantage of natural CDR represented by forest debris.

1.2 Woody biomass burial for carbon sequestration

Wood Harvest Sequestration (WHS) was the name first applied to CDR premised on above- or below-ground sheltered isolation of biomass from trees [5]. However, a related term – Woody Biomass Burial (WBB) [6] – is adopted here as it more clearly denotes a sub-surface structure that also can accommodate woody biomass other than trees.

WBB leverages carbon capture through natural photosynthesis in trees or other woody plants, followed by isolation of dead or fallen biomass in relatively shallow sub-surface cavities in natural geologic materials. The targeted biomass is discarded debris or waste which otherwise would return carbon to Earth's atmosphere either through burning or subaerial decay. In short, WBB integrates biology with geology to accomplish CDR as a nature-based NET.

Sub-surface burial is intended to create and sustain anaerobic conditions which significantly reduce the rate of wood decay relative to aerobic (sub-aerial) conditions. Suppression of wood decay under anaerobic burial is known from independent studies of landfills [7, 8], archeological sites [9], and paleoclimate studies of natural landscape evolution [10].

Indeed, the *Intergovernmental Panel on Climate Change* (IPCC) in 2019 updated its assessment of carbon stocks in harvested wood products to affirm wood buried in a solid waste disposal site as a form of sequestration [11]. As of the 2019 update, IPCC, in effect, recognized WBB as a

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prospective method in which buried wood might retain $\geq 99.9\%$ of its carbon over a 100-year time interval.

The basic concept and environmental premise of WBB were articulated previously [5, 12–14]. Zeng and Hausmann [13] proposed the name "Wood Vault" for a structure that is built to accomplish sustainable storage or sequestration of carbon in harvested wood – including seven (7) different variations of conditions which could qualify as storage or sequestration implementations.

Following the implementation outline suggested by Zeng and Hausmann [13], the current analysis defines an ***Underground Wood Vault (UWV)*** as follows:

> A sub-surface cavity in natural geologic materials which is created by mechanical excavation, filled below ground level with woody biomass and sealed by backfilling, covering and compaction of excavated geologic materials, including a cap elevated above ground level to impede infiltration of water from the surface.

A successful UWV relies upon the co-location of renewable sources of woody biomass with geologic conditions which favor stable, long-term sub-surface containment. However, unlike most schemes for geologic sequestration of carbon – which involve the injection of supercritical CO_2 through high-pressure wells into deep saline aquifers or other receptor strata [2] – a UWV is accomplished in the relatively shallow sub-surface where excavation is uncomplicated.

Several key advantages of a UWV for carbon sequestration are as follows:

- Simple and low-cost technology which is readily available and straightforward to implement using geologic materials at each site.
- Maximum leverage of natural Earth processes for which long-term sequestration durability is empirically demonstrable through geologic examples.
- Avoidance of synthetic or artificial materials – such as plastic, metal, or concrete – which might negatively affect the local ecosystem.
- Optionality to recover the buried biomass if other, beneficial uses of the sequestered carbon become compelling at a later date.

2 Geologic perspective on UWV design

2.1 Overview of geotechnical attributes

WBB depends on near-surface geology functioning as the sequestered carbon container for the UWV. Suitably chosen natural geologic materials should provide long-term containment of the buried biomass and any decomposition products, including CO_2 or methane (CH_4). Therefore, the role of geologic assessments for WBB is to evaluate environmental and geotechnical attributes which maximize the long-term stability and confinement quality of candidate UWV locations.

The main considerations which are expected to affect the long-term durability of a UWV are summarized in Table 1. For the three principal geologic attributes of hydrology, lithology, and seismicity, each candidate UWV site must be evaluated individually and through the use of consistent criteria.

Hydrology pertains both to surface water and groundwater. Understanding the surface environment includes knowledge of annual and seasonal precipitation as well as history and prospects for ponding, flooding, or erosion. The sub-surface environment must be known with regard to where aquifers are located, how they are recharged, and how they control groundwater flow.

Lithology means material grain size and texture as well as the mineralogical composition of soils and bedrock. In addition to grain-size distributions, the degree of compaction (or compactability) influences porosity and permeability. Also, contents of expandable phyllosilicate minerals (especially, smectites) can affect shrink-swell properties of containment materials exposed to variable water cycles.

Seismicity begins with the potential for natural earthquakes but it extends also to the potential for artificial earthquakes. Whereas natural earthquakes are determined by tectonic settings, artificial earthquakes could arise from high-energy anthropogenic activities such as mining, oil and natural gas drilling, and production or waste disposal through deep injection wells.

Zeng and Hausmann [13] noted that anaerobic burial conditions could be accomplished either where WBB was environmentally "dry (desert)"or "perpetually wet (submerged under water)"; "Tumulus (burial mound)" implementations also were mentioned but without quantitative criteria for limits on water content. With regard to sequestration durability, water exclusion is favored by proponents of landfill-analog designs [14] whereas water flooding is favored by some archaeological case studies [9]. For carbon accounting in climate-mitigation models, IPCC [11] recognized slower decay rates for landfill scenarios where isolation from groundwater was a design element, thereby steering many WBB projects toward avoidance of water.

Figure 1 illustrates the geotechnical parameters which must be quantitatively evaluated to establish the sequestration durability of a UWV which is premised on geologic materials as the containers for WBB. The analysis around this simple model is meant to identify boundary conditions for how a UWV is situated, constructed, and monitored for durable carbon sequestration under conditions that exclude free water.

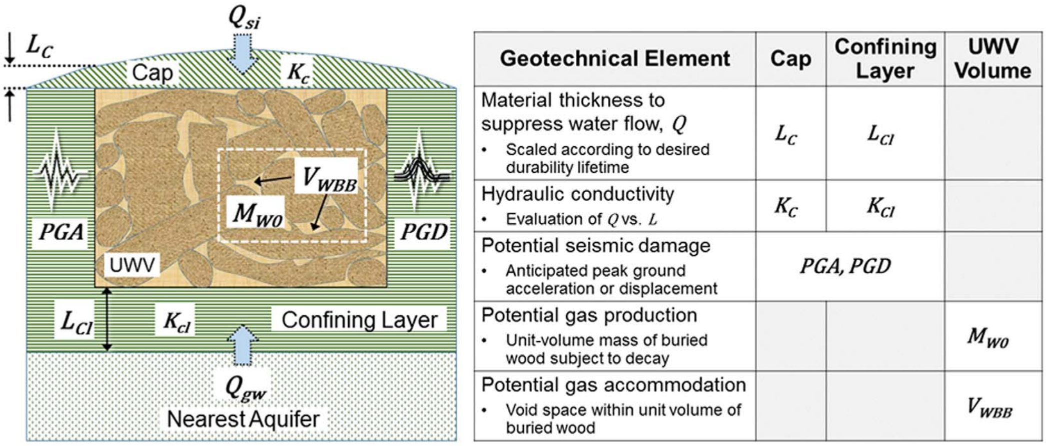
The UWV design (Fig. 1) is comparable to the "underground / pit" concept of Zeng and Hausmann [13] but with a compacted, low-permeability cap deliberately extended above ground level to help divert surface water. The function of the compacted and built-up cap is to discourage surface ponding of water which could accelerate downward water infiltration into the biomass buried below ground.

For the remainder of this analysis, the targeted water content of the UWV interior is defined as ***low-moisture conditions***:

> No water beyond the amounts which can be fully absorbed by geologic materials used as confining layers, backfill in residual voids, and compacted caps at the ground surface.

Table 1. Geotechnical considerations in UWV design.

Geologic attribute	Geotechnical issues	Possible impacts on Underground Wood Vault (UWV) durability	Assessment criteria
1. Hydrology	A. Proximity to surface water	Water infiltration from above	Surface water flow patterns
			Annual and seasonal precipitation
	B. Proximity to groundwater	Water incursion from below	Aquifer locations (vertical and lateral)
			Aquifer recharge and discharge dynamics
	C. Predictability of water movement	Water environment cannot be reliably modelled	Multi-decadal records of precipitation and water-well productivity
2. Lithology	A. Permeability	Materials do (or do not) allow interstitial water or gas flow	Soil composition and texture
			Bedrock composition and texture
	B. Hydraulic conductivity	Materials do (or do not) minimize flow-penetration rates by water	Hydraulic conductivity values for all materials
	C. Plasticity	Materials do (or do not) display selfhealing properties during wet/dry cycles	Liquid limit and plasticity index values for all materials
	D. Sorption capacity	Materials do (or do not) tend to immobilize water or GHG through sorption	Mineral composition, especially abundance of expandable phyllosilicates
3. Seismicity	A. Peak Ground Acceleration (PGA) from shock waves	Shock waves do (or do not) occur frequently	PGA model for 50-year or longer timescale
		Shock waves do (or do not) occur strongly	Wave-amplification potential implied by lithology
	B. Peak Ground Displacement (PGD) from shock waves	Cap fractures admit water from above or release GHG from below	Mechanical response model for site materials
		Sub-surface fractures admit groundwater from below	Geologic evidence for absence of land surface disturbance by earthquake activity



Geotechnical Element	Cap	Confining Layer	UWV Volume
Material thickness to suppress water flow, Q - Scaled according to desired durability lifetime	L_C	L_{Cl}	
Hydraulic conductivity - Evaluation of Q vs. L	K_C	K_{Cl}	
Potential seismic damage - Anticipated peak ground acceleration or displacement	PGA, PGD		
Potential gas production - Unit-volume mass of buried wood subject to decay			M_{W0}
Potential gas accommodation - Void space within unit volume of buried wood			V_{WBB}

Fig. 1. Geotechnical variables for an Underground Wood Vault (UWV).

The aforementioned definition of low-moisture conditions satisfies the carbon-accounting guideline applied to WBB which stipulates "Elimination of fresh water via dry conditions" [6]. Although "dry" is not strictly defined by [6], the criterion is meant to exclude oxygenated, standing-free water as a feature of the UWV.

2.2 Hydrology

The geologic reality is that every UWV could be vulnerable to encroachment by water either from precipitation or run-off at the land surface or from groundwater in sub-surface aquifers. Accordingly, the low-moisture UWV design must optimize separation from water sources while also utilizing stable geologic container materials which resist penetration by water.

Water flow, Q, through geologic media can be approximated through a generalized form of Darcy's Law [15]:

$$Q = AK\Delta_{hp}, \tag{1}$$

where A is the cross-sectional area of flow, K is hydraulic conductivity and Δ_{hp} is hydraulic gradient. A hydraulic gradient is a dimensionless number that represents the relative magnitude of (positive) pressure driving water movement at a specific location.

Different environments affect how values of K and Δ_{hp} are evaluated and used in calculating Q. Values of K and Δ_{hp} depend on whether the medium supporting water flow is a saturated aquifer, an aquitard (also known as an aquiclude or confining unit) adjacent to the aquifer or a surficial soil horizon which can experience alternating periods of saturated and unsaturated conditions.

Hydraulic conductivity varies with properties that control permeability and fluid flow, including average pore diameter (d_p), liquid density (ρ), liquid dynamic viscosity (μ) and gravitational acceleration (g):

$$K = C_p {d_p}^2 \left(\frac{\rho g}{\mu}\right); \quad K_i = C_p {d_p}^2, \tag{2}$$

where C_p is a proportionality constant that varies with the solid medium. For an individual fluid, such as water of a specific composition and temperature, variations often are referenced to the value of intrinsic permeability, K_i. Because d_p is correlated directly with the grain size of the solid medium, K_i and K decrease as the average grain size decreases [15].

At the surface, where vertically downward infiltration through soil dominates, Philip's modification of Darcy's Law applies [16]:

$$Q_{\mathrm{si}} = AK_{\theta\mathrm{si}}\left(\frac{H}{Z}\right), \tag{3}$$

where Q_{si} is the soil-infiltration rate, $K_{\theta\mathrm{si}}$ is the hydraulic conductivity of the water-saturated soil, Z is soil depth and H is the depth of water ponded at the land surface above the soil.

In the sub-surface, where lateral flow dominates, hydraulic gradient is the distance-normalized difference between the hydraulic head at the point of recharge (where water accumulates in an aquifer) and the hydraulic head at the point of discharge (where groundwater flows across an interface or into a different medium). Accordingly, the groundwater flow rate is approximated as,

$$Q_{\mathrm{gw}} = AK_{\mathrm{gw}}\left[\frac{\boldsymbol{h(r) - h(d)}}{\boldsymbol{L}}\right], \tag{4}$$

where K_{gw} is the hydraulic conductivity of the aquifer, $h(r)$ and $h(d)$ are hydraulic head values at the aquifer recharge and discharge points, respectively, and L is the horizontal distance between the recharge and discharge points.

Typical variations of Q with K and Δ_{hp} are shown in Figure 2 which features reference data for aquifers and aquitards in North America [17] and ranges for soils as reflected in a global database [18].

Rainfall and surface runoff create short-lived but steep hydraulic gradients which intermittently saturate soils and infiltrate water downward according to equation (3). In contrast, groundwater flow follows equation (4) where hydraulic gradients are smaller but more persistent. Therefore, reducing uncertainties in the "dry" longevity of the UWV requires reliable knowledge of the hydraulic properties of materials both above and below the UWV confining layer, along with the frequency of intense rainfall and surface flooding.

A favorable UWV confining layer can be expected to possess properties usually associated with aquitards (Fig. 2b) which commonly are compact, clay-rich detrital sediments (Fig. 2a).

2.3 Lithology

For ease of excavation, a UWV is most advantageously located where local geology is dominated by clastic sedimentary bedrock or unconsolidated clastic sediments.

For other variables being constant, and where Δ_{hp} is reliably known, the main differentiator for water flow through geologic materials is K. Therefore, for a low-moisture UWV, a minimal value of K is sought for the layer(s) meant to provide biomass confinement.

The dependence of K on sediment grain size is intrinsic to equation (2) and is more explicitly described by the generalized Hazen approximation [15]:

$$K = C_s {d_{s50}}^J, \tag{5}$$

where d_{s50} is the mean grain size (mm), C_s is a so-called "shape" factor that varies among grain-size intervals and J is an exponent which varies with sediment grain-size maturity (i.e., effectiveness of size sorting). Important grain-size ranges are defined in units of 10^{-3} m as clay (<0.004), silt (0.004–0.0625), and sand (0.0625–2.00).

Equation (5) shows that hydraulic conductivity is expected to be lower in fine-grained sediments than in coarse-grained sediments. Accordingly, aquifers hosted in clastic sediments or sedimentary rocks occur in sandy or gravelly layers whereas aquitards – which confine the spatial limits of aquifers – usually are silty or clayey layers. Therefore, the most effective containment layer for a UWV is expected to be clay-rich (Fig. 2).

2.3.1 *Lithology in suppression of water flow*

Using a re-analysis of data from Benson and Trast [19], Figure 3 illustrates the effect of clay content on three properties of importance for a UWV confining layer: liquid limit, plasticity index, and hydraulic conductivity. Both in Figures 3a and 3b, an empirical statistical-fit model is represented as a dashed line.

Liquid limit and plasticity index, known in geotechnical engineering as Atterberg Limits, reflects the ability of a

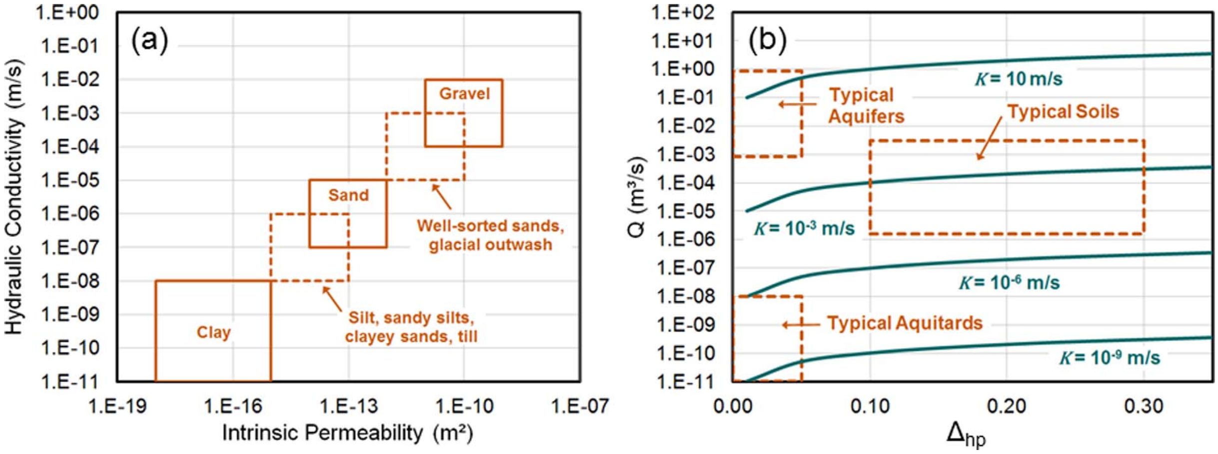


Fig. 2. Darcy flow of water in geologic materials as (a) general trends and (b) specific boundary conditions.

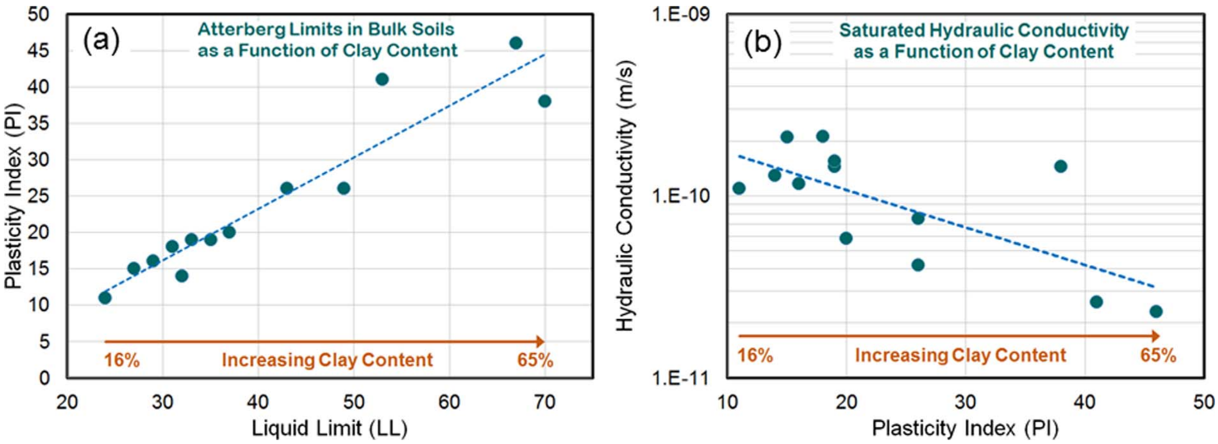


Fig. 3. Variation of hydraulic properties with clay content in terms of (a) Atterberg limits and (b) hydraulic conductivity correlations.

material to hold water and deform under stress without fracturing or otherwise disintegrating. A high liquid limit and high plasticity index both are desirable for a UWV confining layer. For all other variables being constant, both liquid limit and plasticity index increase with clay content (Fig. 3a).

As reviewed above, hydraulic conductivity should be as low as practically achievable to minimize water flow. For all other variables being constant, hydraulic conductivity should be lowest for materials with the highest clay contents (Fig. 3b).

Another important lithologic variable is the abundance of phyllosilicate minerals in the confining layer and cap material. The clay-sized fractions of soils and sediments can include a wide variety of oxide, carbonate, and silicate minerals – most of which do not specifically absorb or otherwise preferentially interact with water. However, phyllosilicates with expandable octahedral layers at the atomic-crystallographic scale are distinguished by their capacities to absorb water molecules within the octahedral layers without decomposing or changing mineral identity. In soil and sedimentary environments, the most strongly expandable phyllosilicates are those in the smectite (montmorillonite) mineral group.

The distinctive behavior of smectites in absorbing interlayer water also affects Atterberg Limits. Materials rich in smectites display substantial shrink-swell properties during cycles of drying and wetting. The capacity to hold water when wet imparts to smectite-rich materials high values of liquid limit and plasticity index. However, drying also causes the otherwise plastic material to shrink and crack – thereby possibly opening pathways for gas migration [20]. Accordingly, the effectiveness of smectite-rich materials in a UWV confining layer requires attention to the degree of wetness as well as the degree of compaction.

Maximum clay swelling is reached below the liquid limit and before free water (conspicuous “wetness”) can persist. Locating biomass within an aquitard/aquiclude unit (which might be in contact with an aquifer) keeps the expandable clays at maximum tightness (minimum permeability) and meets the low-moisture definition for the UWV interior.

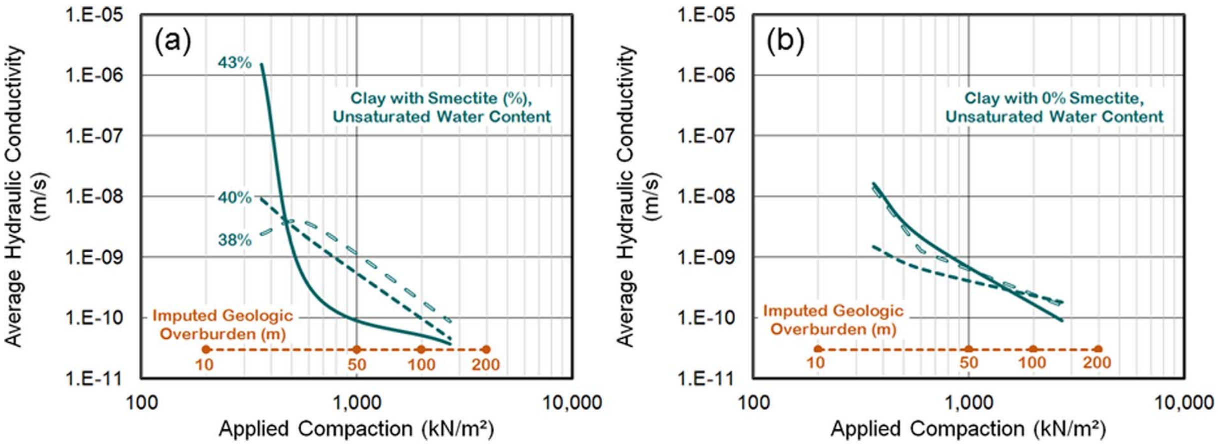


Fig. 4. Effect of compaction on hydraulic conductivity of clay with (a) high smectite content and (b) low smectite content.

Wetting of the UWV cap, not to exceed the liquid limit, should also favor stable swelling of the clays and therefore minimum permeability.

Using representative examples re-analyzed from the data of Benson and Trast [19], Figure 4 illustrates the effect of high smectite content, along with the degree of compaction, on the hydraulic conductivity of clay. Because of strong interactions with water, smectite-rich clays display more sensitivity to compaction than do smectite-poor clays. Significant artificial compaction of loose clay – at $\geq$1000 kN/m^2 – is required to approach the degree of compaction which usually is achieved naturally through accumulated overburden over geologic timescales (i.e., the horizontal dashed lines in Fig. 4).

Indeed, smectite-rich clay does not achieve maximum compaction unless wetted with water (Fig. 5). As applied experimentally by Benson and Trast [19], low compaction represented in Figure 5 is 360 kN/m^2 whereas high compaction is 2700 kN/m^2; experimental water contents are displayed as percentages of the respective values of liquid limit.

Important takeaways from Figures 4 to 5 are as follows:

- Smectite-rich clays display more variable behavior of hydraulic conductivity than do smectite-poor clays.
- Both for smectite-rich and smectite-poor clays, high compaction, in addition to wetting with water, is required to achieve the lowest possible values of hydraulic conductivity.
- Both for low and high degrees of compaction, minimum values of hydraulic conductivity in clays occur only at water contents that are approximately $\geq$50% of the liquid limit.

The compaction of natural confining layers is preordained by geologic history, based on depositional environments and accumulated overburden through timescales of thousands to millions of years. However, the compaction of materials used as backfill and caps in UWV structures (Fig. 1) should be addressed during UWV construction. Without compaction, backfilled cap material can be expected to have relatively high hydraulic conductivity. Furthermore, backfilled cap material that is rich in smectites will not achieve and maintain optimum plasticity unless kept wet at values that approach – but do not exceed – liquid limits.

2.3.2 Lithology in gas containment

Sorption capacity for gas is another desirable attribute for geologic materials which are intended to act as confining layers – including uncompacted material used as backfill within the residual void spaces of the buried biomass (V_{WBB} in Fig. 1). Void space is not a design target but is a consequence of imperfect packing of the buried biomass. Void spaces of $V_{\mathrm{WBB}} = 26\%$ to 65% (average 41%) are typical of stacked wooden logs [21] although the actual V_{WBB} for a specific UWV is expected to vary with the physical characteristics of the woody biomass and compaction methods. In a model UWV, $V_{\mathrm{WBB}} = 25\%$ to 50% can be considered indicative of a reasonable range of compaction outcomes.

Because CO_2 and CH_4 are expected to be slowly evolved products of wood decay – even under anaerobic conditions – impeding or arresting migration of those gases is a highly desirable quality for the confining material.

The gas pressure, $P_{\mathrm{GHG}t}$, which might develop from CO_2 and CH_4 within the UWV at the post-burial elapsed time, t, can be predicted as,

$$P_{\mathrm{GHG}t} = \left[M_{\mathrm{GHG0}}\, e^{-k(wd)t}\right] Z_{\mathrm{GHG}} R \left[\frac{T}{V_{\mathrm{WBB}}}\right], \qquad (6)$$

where M_{GHG0} represents the moles of GHG per unit mass of the WBB at burial ($t = 0$), t is post-burial elapsed time, $k(wd)$ is the rate constant for wood decay, Z_{GHG} is the compressibility factor for the GHG, R is the ideal gas law constant, T is the temperature (298 K) and V_{WBB} is the fractional void space in a unit volume of the closed UWV.

Figure 6 shows indicative $P_{\mathrm{GHG}t}$ trajectories for different sets of assumptions. Because IPCC [11] recognized a limit of 8.8% by weight for probable wood decay in a low-moisture UWV, application of a constant decay rate to that limit, over 100 y or 1000 y, respectively, defines the pressure-versus-time relationships in Figure 6a for alternative values

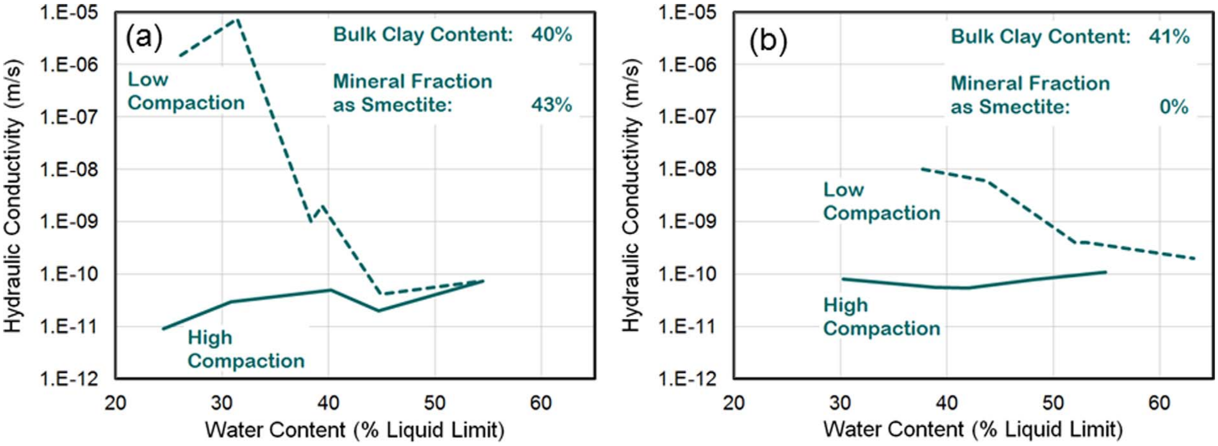


Fig. 5. Effect of water and compaction on hydraulic conductivity in (a) smectite-rich clays and (b) smectite-poor clays.

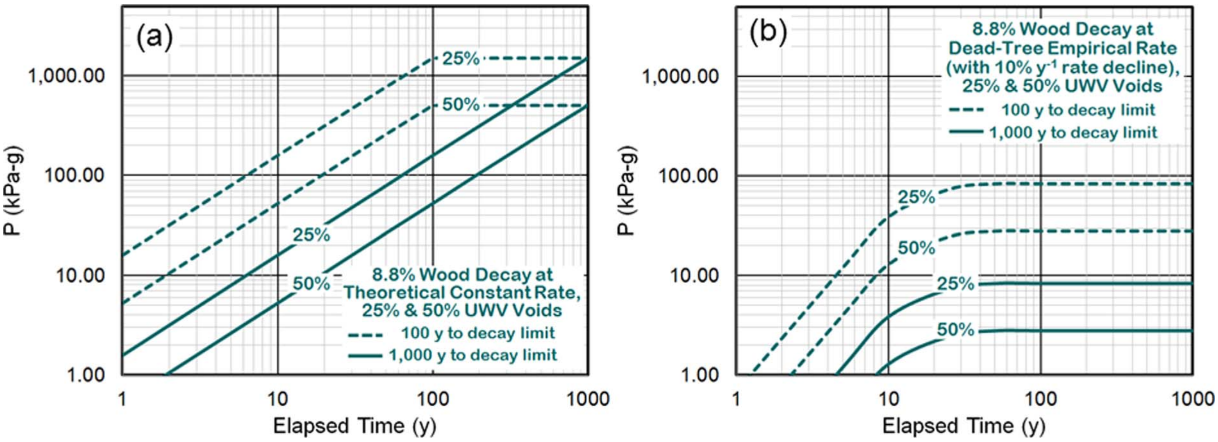


Fig. 6. Scenarios for gas pressure build-up in a UWV according to (a) constant-rate decay and (b) declining-rate decay.

of $V_{\mathrm{WBB}} = 25\%$ and $V_{\mathrm{WBB}} = 50\%$. (The wood decay rate implicit in the highest pressure-versus-time trajectory in Figure 6a is approximately 1×10^{-4} mol CO_2 g^{-1} d^{-1}). Results in Figure 6a provide guidance for the high-end pressure conditions if no additional information was available about actual wood decay rates or gas suppression.

However, real measurements of wood decay rates suggest that high-end pressures in Figure 6a are not the most likely outcomes. Specifically, Kipping and co-workers [22] found, for a wide variety of dead trees, average empirical gas-emission rates of approximately 5×10^{-6} mol CO_2 g^{-1} d^{-1} and 2×10^{-9} mol CH_4 g^{-1} d^{-1} for aerobic conditions. When the empirical value for CO_2 evolved from dead trees under aerobic conditions [22] is adopted as the more likely initial decay rate, in combination with an assumption that the aerobic-style decay rate will decline by 10% per year after wood burial, the alternative pressure-versus-time curves become those in Figure 6b. In the latter decay scenario, using empirical aerobic rate with continual decline, gas pressure should be expected to stabilize (become static) after approximately 40 y. (The concept of gas-pressure stabilization after pit closure is analogous to municipal landfills where post-closure gas pressures – mainly attributable to CH_4 – tend to stabilize at <300 kPa after 10 y [23].)

Lithology also plays a second role in gas containment. Phyllosilicate minerals which are common in clay-sized fractions of soils and sediments are known to be active in the sorption of gases [24], including CH_4 [25] and CO_2 [26], as illustrated in Figure 7. The elevated temperatures and pressures used in the experiments summarized in Figure 7 reflect waste-management research interests in understanding the performance of phyllosilicates under warm conditions with elevated gas pressure, as might accrue from exothermic chemical reactions in buried waste other than wood debris.

Increasing sorption capacities with increasing pressure show that phyllosilicates can remain effective sorbents for GHG in a UWV; the tipping point at approximately 8 MPa (Fig. 7) is equivalent to overburden from a highly compacted clay layer of roughly 400 m thickness which far exceeds the depth range of 5–10 m which is anticipated for a UWV.

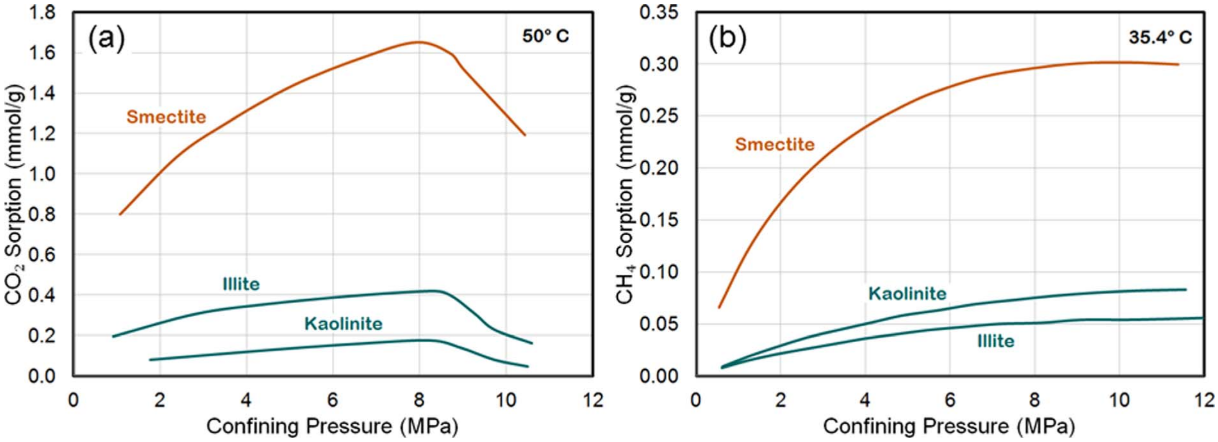


Fig. 7. Gas sorption by phyllosilicate minerals for (a) CO_2 and (b) CH_4.

The larger body of evidence from geologic containment of CO_2 and CH_4 shows that sorption capacity further increases as temperature decreases [24–26] so that a UWV maintained at a moderately low temperature (for example, 298 K / 25° C or less) should favor even greater gas sorption by backfilled clay than is shown in Figure 7.

Although some less abundant phyllosilicates, such as saponite and palygorskite, exhibit even higher sorption capacities for CO_2 [23], smectite is the most common phyllosilicate with the highest sorption capacities both for CO_2 and CH_4 (Fig. 7). Therefore, smectite would be a desirable gas-sorption component of a candidate UWV confining layer as well as backfill and cap material.

For typical wood with a carbon stock of 50% by mass, total decay of 8.8% would produce the equivalent of 3664 mmol of CO_2 or CH_4 (or a mixture of the two) from each kilogram of wood. At the lowest sorption pressures depicted in Figure 7, the gas sorption by smectite could be 800 mmol/kg for CO_2 or 66 mmol/kg for CH_4. Therefore, backfilling of UWV voids with smectite-bearing clays could not be expected to sorb and immobilize all decay gas although possibly up to approximately 20% of evolved gases might be so captured.

2.4 Seismicity

Because a UWV is meant to endure for hundreds of years or longer, ground shaking by earthquakes is highly undesirable. The two main seismic risks are sub-surface fracturing of the confining layer and surface fracturing of the cap.

Sub-surface fracturing might allow groundwater to breach upward into the UWV whereas surface fracturing of the cap probably would allow surface water to breach downward. In either case, entry by oxygenated free water could change the low-moisture UWV containment volume into a wet volume where biomass decomposition rates could multiply. Surface fracturing of the cap could also allow the atmospheric escape of any GHG decay products trapped below ground.

As always in assessing seismic hazards, attention must be paid to differences between earthquake intensity and associated earthquake damage [27–30]. In many situations, earthquake damage from a given earthquake intensity varies with geology, including whether a structure is founded upon solid bedrock or loose sediments.

The key attributes in evaluating seismic risk for a UWV site are as follows:

- Maximum, long-term (50 years or longer) expectation for Peak Ground Acceleration (PGA).
- Seismic-wave damage potential, based on the relationship of PGA to Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD).

Both for surface and sub-surface structural damage, PGD is one of the most important earthquake consequences to predict. For seismic damage to buried pipelines, Pineda-Porras and Ordaz [29] found a predictor of PGD based on PGA and PGV. A separate, calibrated ground-shaking model by Evans [30], found related relationships for seismic damage:

- No damage: PGA $\leq$ 3.9% g PGV $\leq$ 0.034 m/s
- Very light damage: PGA 3.9%–9.2% g PGV $\leq$ 0.081 m/s
- Light damage: PGA 9.2%–18% g PGV $\leq$ 0.16 m/s,

where g is the gravitational acceleration (average value of 9.81 m/s^2).

Using a re-analysis of earthquake data compiled by Ye and co-workers [28], Figure 8 shows how PGD is predictable from PGA and PGV. Both in Figures 8a and 8b, an empirical statistical-fit model is represented as a dashed curve. The parameter, PGV^2/PGA, follows the findings of Pineda-Porras and Ordaz [29], and the boxes marked as indicative damage limits follow the findings of Evans [30].

Based on data in Figure 8, the ideal (but perhaps rare) location for a UWV would have a 50-year (or longer) value of PGA < 3.9% g although acceptable values could range up to PGA < 18% g; a PGA value of <9% g would be a reasonable target.

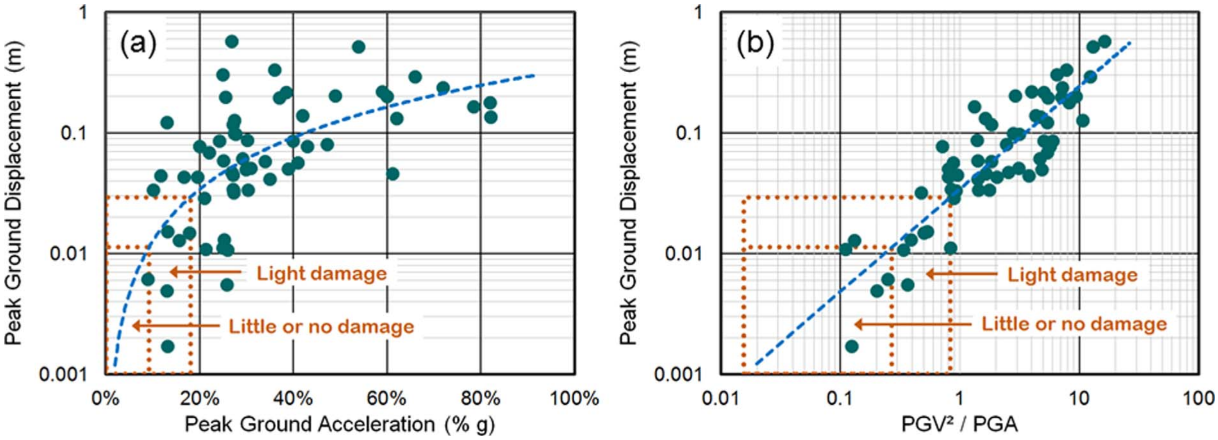


Fig. 8. Earthquake damage potential versus strength of ground shaking for (a) peak acceleration and (b) velocity-adjusted acceleration.

3 Recommendations for sequestration durability

3.1 Durability and reversal risk

For proposed NET and CDR methods, two concepts are central to evaluation from a carbon-accounting perspective [31]:

- ***Durability*** – Length of time that sequestered carbon will be isolated from environmental re-circulation cycles.
- ***Reversal Risk*** – Likelihood and consequence of a premature or unplanned failure of carbon containment.

In principle, durability is predictable based on science- and engineering-based quantitative analysis of a specific CDR process and system. Reversal risk would be logically related to limitations or uncertainties in predicted durability.

This paper emphasizes the assessment of durability, based on a set of geologic principles and empirical data, and views reversal risk as significant only if deviations occur with respect to recommended geologic containment guidance for the UWV. In effect, reversal risk should be expected to be very low if recommended UWV design criteria are applied and maintained.

3.2 Recommended durability conditions

As reviewed above, UWV durability depends on the following principal attributes:

- Creation and maintenance of low-moisture conditions for buried biomass.
- Isolation of buried biomass from surface water infiltration and groundwater incursion over time.
- Containment of CO_2 and/or CH_4 evolved during biomass decay over time.
- Preservation of containment integrity against disruption by seismic waves.

In practice, values of key geologic variables span specific ranges which imply different possible values for UWV durability. Therefore, specific durability can be expected to vary with the geologic setting, design, and construction of each UWV.

For the isolation of buried biomass from water, the main variables are intrinsic permeability and hydraulic conductivity of the below-ground confining layer and the above-ground cap. Depending on which phyllosilicates might dominate the clay-based confining materials, related variables are the degree of compaction and the degree of water saturation of the container materials. For planning a UWV, Figure 9a can be used by reading horizontally along the time axis to the desired durability lifetime (for example, 100 y) and then vertically upward along the water-penetration axis to intersect the required hydraulic conductivity of the confining material. Accordingly, a 100-y durability lifetime against water incursion implies confining layers of 1–3 m thickness (Fig. 9a).

Figure 9b can be used to plan for gas confinement except that the key consideration is the relationship between the gas-pressure curve and the confining pressure curve. To be clear, the confining-pressure curve in Figure 9b represents a highly-compacted, water-saturated clay (specific gravity of 2.8) which is representative of the materials described in Section 2. As indicated in Figure 9b, 100-y durability of gas containment would require a UWV compacted cap of approximately 3.2 m thickness.

For all geologic parameters reviewed in this paper, summary guidance for a durable UWV design is provided in Table 2.

3.3 Monitoring, reporting, and verification

Standards and guidance for carbon accounting [31] also require auditable evidence for Monitoring, Reporting, and Verification (MRV) of each carbon sequestration project. For WBB implemented through a low-moisture UWV,

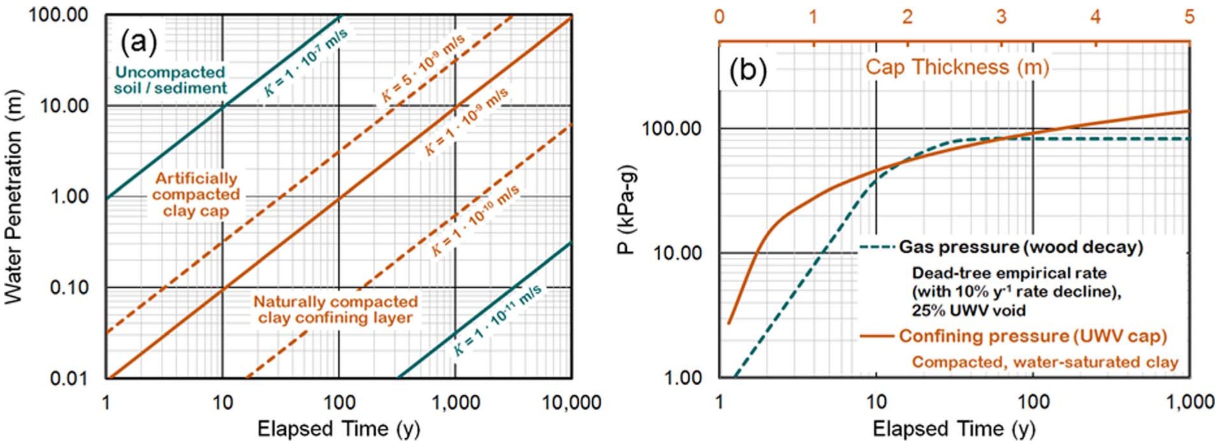


Fig. 9. Boundary conditions for UWV sequestration durability in terms of (a) water penetration and (b) evolved-gas containment as a function of gauge pressure.

Table 2. Guidance values for UWV durability design.

Variable[A]		Units[B]	Target value for sequestration durability[C]		MRV[D] notes
			100 y	1000 y	
K_{gw}	Groundwater hydraulic conductivity	m/s	$\leq 1 \times 10^{-9}$	$\leq 1 \times 10^{-10}$	These variables address the groundwater-incursion suppression requirement.
$\mathrm{L_C}$	Confining layer thickness	m	1 to 3	10 to 30	These target values apply to the sub-surface confining layer which separates the UWV from the nearest aquifer.
$\mathrm{K_{si}}$	Surface hydraulic conductivity	m/s	$\leq 5 \times 10^{-9}$	$\leq 5 \times 10^{-10}$	These variables address infiltration by surface water.
$\mathrm{L_{Cl}}$	Cap thickness	m	3 to 3.2	3.5 to 5	These target values apply to the surface cap of sediments or soils covering the top of the UWV.
PGA	Peak ground acceleration	% g(m/s^2)	9% (0.88)	9% (0.88)	This variable defines the maximum expected seismic energy input through ground shaking.
PGD	Peak ground displacement	m	0.012	0.012	This variable defines the maximum expected size/shape distortion of the UWV created by seismic energy.
$\mathrm{V_{WBB}}$	Void space around buried wood	Percentage of total volume	25%	50%	Gas containment is maximized if the void space is at least partially filled by loose, smectite-rich clay.

[A] Refer to Figure 1 for physical context.
[B] Abbreviations: g – gravitational acceleration ($1\ g = 9.81\ \mathrm{m/s^2}$); m = meter; s = second; y = year.
[C] Durability is the length of time that sequestered carbon will be isolated from environmental re-circulation.
[D] Monitoring, verification and reporting (for carbon-accounting audits).

the following steps are recommended to make each project auditable to MRV standards prescribed for durability:

1. Geologic analysis of the setting for the UWV, including hydrology, lithology, and seismicity.
2. Documented values of key hydrologic properties, including surface water and groundwater sources and sinks, hydraulic gradients, and hydraulic conductivities of confining materials.
3. Documented values of key lithologic properties of confining materials, including physical texture, grain-size distribution, mineral composition, liquid limit, plasticity index, and shrink-swell capacities.
4. Documented values of key seismic characteristics, including expected peak ground acceleration and peak ground displacement over a specified time period.
5. Estimations of gas pressure that might arise from biomass decay after closure and capping of the UWV.

6. Analysis of adequacy of confinement-material thicknesses to suppress water incursion and gas escape for the targeted durability lifetime.
7. Post-closure physical and chemical monitoring of the UWV structure to validate stability and sequestration performance relative to model predictions.

4 Conclusion

Carbon sequestration through WBB, as implemented in a UWV, is a plausible and even attractive nature-based NET to accomplish CDR. However, there has been little to no quantitative assessment of the geologic conditions required to predict and assure the sequestration durability of a UWV.

Basic geologic principles, supported by appropriate experiential analogs, can be used to estimate boundary conditions for the durability of an individual UWV. To achieve an auditable MRV plan for a UWV, the UWV design should include a quantitative assessment of geologic attributes which define the site's hydrology, lithology, and seismicity as well as estimates for anticipated gas pressure evolved from any decay of the buried biomass.

Because of their self-sealing and gas-sorption capacities, fine-grained natural clays – especially those with high smectite mineral contents – are desirable confining materials. However, effective use of smectite-rich clays must pay careful attention to the degree of compaction and water content; highly compacted and water-wetted clays are expected to be the most effective confining layers.

Although the durability of each UWV must be assessed based on individual characteristics, for targeting 100-year sequestration durability, useful planning ranges for subsurface confining layers and surface cap layers probably are in the range of confinement-material layer thickness of approximately 1–3 m.

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