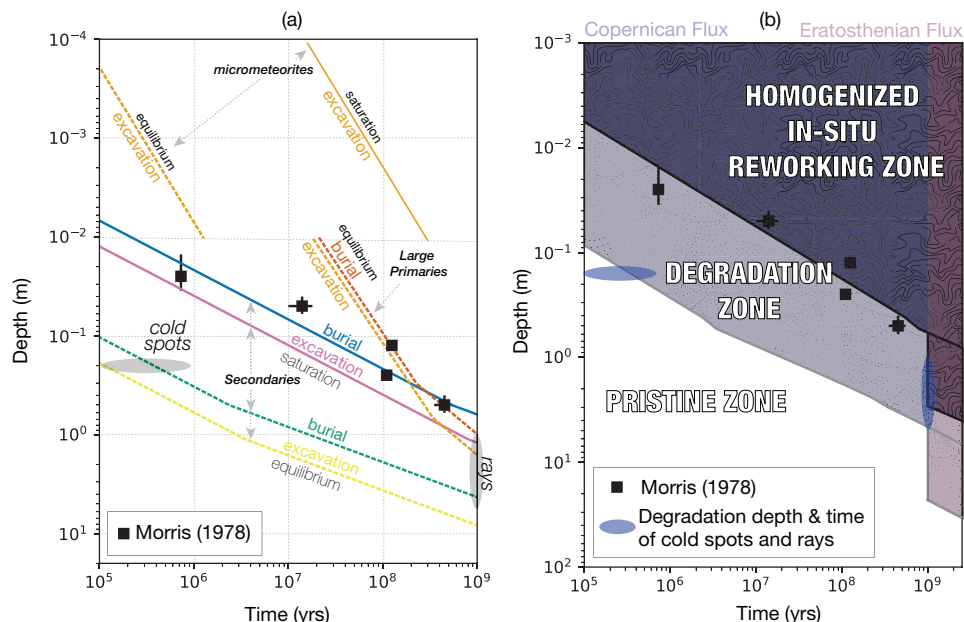


**IMPACT GARDENING DOES NOT PROTECT SOUTH POLAR ICE.** E. S. Costello<sup>1,2</sup>, R. R. Ghent<sup>3</sup>, P. G. Lucey<sup>1</sup>  
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**Introduction:** “Impact Gardening,” or the process by which impacts mechanically churn the lunar regolith, plays a crucial role in the evolution of water ice in permanently shadowed regions at the lunar poles. Ice at the uppermost surface is ephemeral, destabilized by micrometeorite impacts, sublimation, and photodissociation; however, these antagonists do not penetrate more than a few cm into the regolith. Buried ice may be preserved at depth. For example, statistically shallow depth-diameter ratios of south polar craters may suggest buried ice fills these craters [1]. Gardening has been suggested as shield for ice [2] because protective area forms more quickly than destruction by the same impact (for every destructive impact of area  $R^2$ , the impact produces a protective ejecta of area  $(2R)^2 - R^2$ , and protection accumulates three times faster than destruction). However, disruption of that protection proceeds at a rate

proportional to the thickness of the protective layer, not area. Because impactor sizes on the Moon follow a steep cumulative power law slope, small impacts are exponentially more frequent than large impacts. A thin ejecta blanket is exponentially more likely to be penetrated by small excavations than a thick ejecta blanket is likely to be produced by a large impact. But what are the relative rates of protection and disruption?

If excavation is faster than burial, then the disruptive processes which are otherwise restricted to the uppermost surface will be felt throughout the column over time and all ice to the gardening depth can be considered to have undergone significant physical disruption. We model the rate of excavation and burial by impact gardening. Our model quantitatively demonstrates the vigorous mixing of relatively slowly accumulating ejecta with underlying material by small impacts (**Figure 1**).



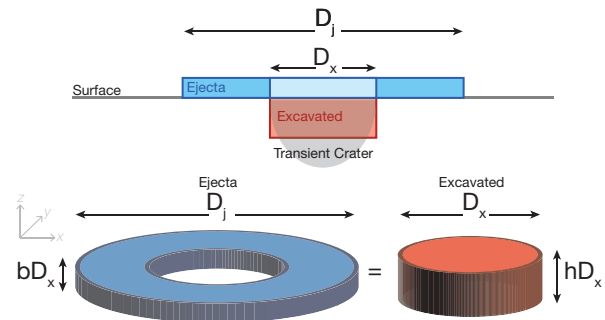
**Figure 1:** These plots show increasing gardening depth as a function of increasing time and the relative rates of excavation and burial. **a)** Model gardening depth over time predictions are shown for gardening by the flux of larger than 1 cm primaries, micrometeorites, and the flux of secondary impacts [3]. Burial is calculated by scaling the area of ejecta blankets assuming 90% of ejecta is emplaced within 1 crater radius. ‘Saturation’ is defined at 99% model probability. ‘Equilibrium’ is defined at >2% model probability. **b)** The “homogenized in-situ reworking zone” is defined by the sum of excavation and burial by primaries and secondaries at saturation (99% probability) as a function of time. The “Degradation Zone” is defined as the sum of excavation and burial by primaries and secondaries at equilibrium (2% probability) as a function of time. We extend the gardening calculation to 2.5 Ga by multiplying the Copernican rate by a factor of 5 between 1 and 2.5 Ga [7]. Results are plotted with data from Morris [8] (the reworking rate implied by Apollo cores) and the degradation rate and depth of density anomalous cold spots [9] and crater rays [10].

**Model:** In this work we adapt an analytic model [3,4] to calculate a burial rate under ejecta blankets to compete with a previously modeled excavation rate. The analytical model describes the frequency and extent to which a point is affected by a Poisson distribution production of truncated paraboloids (in the case of excavation) and hollow cylinders (in the case of burial). The diameter of the paraboloids and cylinders is controlled by impactor to crater scaling laws [5] and reasoning based on the depth of excavated (vs. disrupted or compressed) material in the transient crater [6]. The thickness of the hollow cylinder which represents ejecta in the model is calculated by assuming conservation of mass between the excavated and emplaced volumes, an inner diameter equal to the apparent crater diameter, and an outer diameter equal to the extent of the continuous ejecta blanket (**Figure 2**). For the calculations presented here we assume continuous ejecta extends to 1 crater radius away from the crater rim and accounts for 90% of the ejecta mass with ejecta and target having the density of regolith.

**Results:** We sum the results of the gardening model burial and excavation rates (**Figure 1a**), and define the “in-situ reworking zone” as the depth of geometric saturation gardening (>99% probability) and the “degradation zone” as the depth of the equilibrium gardening (> 2% probability) [11] (**Figure 1b**). Saturation gardening (the in-situ reworking zone) is vigorously mixed and material within this zone can be considered to have spent significant amounts of time directly exposed to space. Material within the degradation zone is likely to have seen some physical disruption associated with impact cratering, but has not necessarily spent significant time cycled to the uppermost surface. We also extend the gardening predictions back to 2.5 Ga by assuming a maximum of a factor of 5 increase in the impact flux between 1 and 2.5 Ga [e.g., [7] describe a factor range of 2 to 5].

**Discussion:** It is unlikely that coherent ice deposits will have been shielded by sufficiently thick burial over time without also being pulverized and mixed with regolith. If coherent deposits exist, they must have been lucky, buried under a thick blanket of regolith near a large crater [12] (however, the depositional environment below the ejecta of a large crater may itself be disruptively energetic via, e.g., ballistic sedimentation: [13, 14]).

Farrell et al. [15] argued that ice is ephemeral at the uppermost surface, even in permanently shadowed regions. Ice anywhere within the vigorously mixed in situ reworking zone can be considered to have spent significant time at the unstable uppermost surface. Thus, ice mass that may have existed within the in-situ reworking zone (~ 1 meter deep) has been depleted



**Figure 2:** Schematic illustration of the geometry employed to model ejecta coverage. We model ejecta volume as a tube and excavated volume as a cylinder.

over the last billion years and is likely heterogeneously distributed, much like layers in the Apollo cores.

The depth of the degradation zone represents regions of mechanical disturbance. Ice within the degradation zone, if present, will be pulverized, and it is unlikely that we will discover coherent deposits at depths shallower than the interface between the degradation zone and pristine zone. Over the last 1 Ga the degradation zone has reached 4 to 5 m deep. Ancient ice deposits, if they exist at a few meters depth [e.g., 2], have been pulverized and churned to the surface by gardening over the Copernican era.

Explorers should expect that the average South Polar terrain in permanent shadow may contain ice, but mostly highly disrupted and mixed with regolith, with few clasts of coherent ice. In a large depositional environment, such as the base of a crater wall or the depths of a large crater, coherent ice may have been preserved against disruptive gardening.

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