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Cleanup goals for petroleum-contaminated pastures according to oil density, concentration, and soil type

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Abstract: The common 1% oil cleanup criterion was tested for pasture production according to oil type and concentration, in soil types frequently contaminated in southeastern Mexico. Reductions in aerial biomass of *Brachiaria humidicola* were measured over six months in soils contaminated with crude oils of varying grades (light, medium, heavy, and extra-heavy). Dose-response curves for heavy crude-contaminated soils showed acceptable criteria (90% pasture) of 0.71, 0.56, 1.23, ~0.20 and < 0.10% oil for an Arenosol, Vertisol, Gleysol, Fluvisol and an Acrisol, respectively. Generally, for all crude oils, the 1% level resulted in pasture reductions of ~20–70, ~25–60, ~50–65, and ~35–65% in the Arenosol, Vertisol, Fluvisol, and Acrisol, respectively. Still, in the Gleysol it was variable (reduction of ~10% to an increase of ~15%). Thus, the 1% oil cleanup criterion may be suitable for some soils with large amounts of smectite clays and organic matter (such as Gleysols). Still, for most soils, it may not be strict enough to prevent soil fertility deterioration, and soils with large amounts of non-smectite fines may be particularly impacted. Therefore, lower cleanup levels need to be considered, as well as low-cost regenerative agricultural practices to recover soil fertility in contaminated soils, when these cleanup levels are not achievable.

Keywords: remediation; hydrocarbons; 1% rule; water repellency; compaction

The first studies to establish cleanup limits for contaminated soils were conducted by the American Petroleum Institute, providing a technical basis for proposing the first cleanup legislation in the US (Deuel 1991). Deuel (1991) evaluated old production sites, mainly in the southern US, where drilling cuttings had been incorporated into the soil. Soil treatment or natural attenuation has recovered many sites for agricultural use. Sites with < 1% of total petroleum hydrocarbons (TPH) showed no impacts, or they were only slight and lasted no more than one growing season. This criterion was then adopted by the state of Louisiana, a central oil-producing state, in the first legislation on soil cleanup criteria. This was later adopted by Texas and other US states and used as a technical reference in other countries (Nakles 2001).

Since approximately 1995, remediation guidelines in the US for hydrocarbon-contaminated sites have focused on human health risk-based criteria (Nakles 2001). This was also influential in establishing cleanup criteria in many developing countries due to the perception that the US was an advanced country with a strong, developed economy and prominent academic institutions. It was considered that the methods for establishing cleanup criteria for contaminated sites used in the US were probably among the best in the world and worth copying.

However, the social structures that made this a working methodology in the US are absent from many developing countries; there are critical differences with respect to resource ownership, property size and economic development. In the US,

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most crude oil production occurs on private land, and the landowner typically holds mineral rights to the underground oil deposits. Landowners grant licenses to petroleum development companies and receive royalties from the production, which can be substantial and exceed earnings from agricultural or livestock production. The property owner may be much more interested in oil production than in agricultural activities. Some soil contamination may be tolerated, as long as the risk to human health is minimal. This human health-based risk approach is adequate for managing contaminated sites and their remediation, and may also maximise profits for landowners in the US.

Conversely, in many petroleum-producing developing countries (e.g., Mexico, Venezuela, Colombia, Brazil, Nigeria, India, Malaysia, Indonesia), oil is not a private good but a public resource, managed by the government (Sovacool 2010). Petroleum is produced by state-run companies or through concessions to private companies, typically with little to no compensation to landowners, who often lack a direct financial interest in petroleum production. When spills occur, landowners are more concerned about site remediation, not only for human health risks, but also for soil fertility and agricultural/livestock production. Cleanup criteria based exclusively on human health risks may be inadequate to protect soil fertility and agriculture, and fail to protect the property owners' financial interests.

In many environmental agencies in Mexico, people believe that if human health is protected at remediated sites, the regulations are also strict enough to conserve environmental resources, such as soil fertility and groundwater – a supposition not grounded in fact (Mendezcarlo and Lizardi-Jiménez 2020). Research has shown that soil fertility can be affected at oil concentrations that are not toxic (Adams et al. 2016, Álvarez-Coronel et al. 2023). In Mexico, the US and Asia, sites with burnt or very weathered oil in sandy soil, severe water repellency has been found even at low hydrocarbon concentrations, < 3 000 mg/kg (Adams et al. 2016, Zheng et al. 2021). Álvarez-Coronel et al. (2023) demonstrated the susceptibility of kaolinite-rich clayey soils to develop compaction problems, especially when contaminated with heavy oil.

Additionally, some studies have focused on the relationship between oil concentration and plant impacts, especially seed germination and plant establishment of forage crops (Barua et al. 2011, Hernández-Valencia et al. 2017). In a few cases, some evaluation of pasture production (or lack thereof) has been measured in contaminated soil (Rivera-Cruz and Trujillo-Narcia 2004, Zavala-Cruz et al. 2005). These studies were in marshy soils (Gleysols) contaminated with heavy, weathered oil, in which a dose-response curve was useful in establishing possible cleanup criteria based on soil fertility and pasture production. These investigations have been conducted in soils from Tabasco state and the adjoining southern part of Veracruz state, where contaminated sites are frequently located in marshy pastures that have suffered from historic contamination. It is estimated that ~600 ha of pasture lands have been affected by heavy oil contamination in this area (Álvarez-Coronel et al. 2023). These studies generally indicate that a range of about 0.25–0.40% oil is low enough to preserve 90% of pasture production in these floodable areas contaminated with heavy, weathered oil (Rivera-Cruz and Trujillo-Narcia 2004, Zavala-Cruz et al. 2005). It is noteworthy that this is approximately two-thirds less than the original proposal by Deuel (1991) for agricultural protection.

In the present study, this strategy was continued, but with a variety of soils from the region, including sandy soil from the coastal area, several soils from an alluvial floodplain, and soil from a Plio-Pleistocene terrace. The objective was to systematically test the 1% rule for a variety of soils contaminated with different kinds of crude oil, and to develop dose-response curves for pasture production in the predominant soils from the southern petroleum-producing region in Mexico, in soil with heavy crude oil (characteristic of oil spills in the region), to establish cleanup criteria based on soil fertility and agricultural production.

MATERIAL AND METHODS

Sampling sites and preparation. Soil samples were collected in Tabasco state (southeast Mexico), which has a tropical monsoon climate with rainfall all year (Am, Köppen classification system). The area has an average annual precipitation of ~ 1 800 mm and an average annual temperature of ~ 26 °C (Ruíz-Álvarez et al. 2012). The soils were tentatively classified in the World Reference Base (WRB 2022) as Arenosol, Vertisol, Gleysol, Fluvisol, and Acrisol, based on the soil profiles and in accordance with the methodology proposed by Palma-López et al. (2007). The approximate equivalent classifications in the United States Department of Agriculture System (SSS 2022)

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would be Psamment, Vertisol, Gleysol, Fluvent, and Ultisol, respectively. Table 1 shows the location of each sampling site and some relevant characteristics of the sites. It is worth noting that all of the collection sites are located in or very near areas (within 500 m) that have been reported to be contaminated by petroleum spills. All sample sites were located in western Tabasco state, Mexico, within the Tonalá River watershed, which borders Veracruz state.

A simple, directed sampling was conducted to a depth of 30 cm, as this is the most important depth for the development of roots in crops and pastures. Straight shovels were used to collect ~60 kg of soil from each site. The material was placed in gunnysacks for transfer to the laboratory.

Selection and characterisation of crude petroleum. For the dose-response study on oil concentration, heavy crude oil was used from well No. 1459 of the Texistepec Mining Unit (Veracruz). Oil density (°API) was determined according to the method ASTM D 1298-85, using an ASTM 52HH 9/21 hydrometer for heavy crude (ASTM 2005). Petroleum fractions were separated by differential extraction, as described by Karevan et al. (2022). Heavy oil was selected to represent older, historic spills in the region (Tabasco, Veracruz), which have undergone considerable weathering in the tropical environment.

To test the 1% TPH cleanup limit proposed by the API, additional crude oils were also examined (Figure 1, Table 2). For the extra-heavy crude oil, direct density measurement by hydrometer was not possible due to its very high viscosity, and the dilution-extrapolation method was employed (Alegría-Hernández et al. 2019).

Soil contamination. The soil was dried, ground, sieved, and homogenised, and then contaminated with crude oil at concentrations of 1, 2, 4, and 8% (*w*/*w*, dry), with triplicates for each concentration and an uncontaminated control. Each experimental unit (1 kg) was put into a cut-off 2 L bottle, and the base of each was perforated to facilitate water infiltration. The bottles were partially buried in a silty-sand backfill, allowing for capillary uptake of moisture from the underlying soil.

Pasture bioassay. *Brachiaria humidicola* (Humidicola grass) was selected as one of the most

Table 1. Site characteristics, sampling coordinates, and chemical/physical properties

Variable	Arenosol (Psamment)	Vertisol (Vertisol)	Gleysol (Gleysol)	Fluvisol (Fluvent)	Acrisol (Ultisol)
Description	Coastal sandy soil. Pasture and coconuts.	Gilgai micro-relief. High smectite clay content. Poor internal drainage. Pasture, some maize.	Seasonally flooded. Vertical properties. High smectite clay content. Poor internal drainage. Pasture, Savannah Oak (Macuilís).	Rich alluvial soil. Natural river levee. Cacao, bananas, maize, pasture, sugarcane, etc.	Weathered Plio-Pleistocene terrace. Sandy-clay texture. Kaolinites and Fe/Al oxides. Pasture, pineapple, citrus, sugarcane.
Sampling coordinates (UTM – 15Q)	2013938N 393126E	2001746N 406444E	2002323N 406617E	2001587N 406574E	1967239N 399458E
Texture	Loamy Sand	Clay (silty)*	Clay	Clay	Clay
Sand (%)	87.2	0.7	25.8	6.8	37.8
Silt (%)	3.7	39.3	21.3	34.3	12.0
Clay (%)	9.0	60.0	52.8	58.8	50.2
Organic carbon (%)	0.87	2.20	2.84	1.33	4.29
Field capacity (%)	20	37	37	37	32
Cation exchange capacity ($mmol_+$/kg)	31	318	357	214	123
pH	6.7	7.2	7.1	7.0	5.4
Electric conductivity (dS/m)	0.31	0.15	0.01	0.01	0.41
Bulk density (g/cm^3)	1.4	1.1	1.1	1.1	1.1

*on the border between clay and silty clay texture classifications

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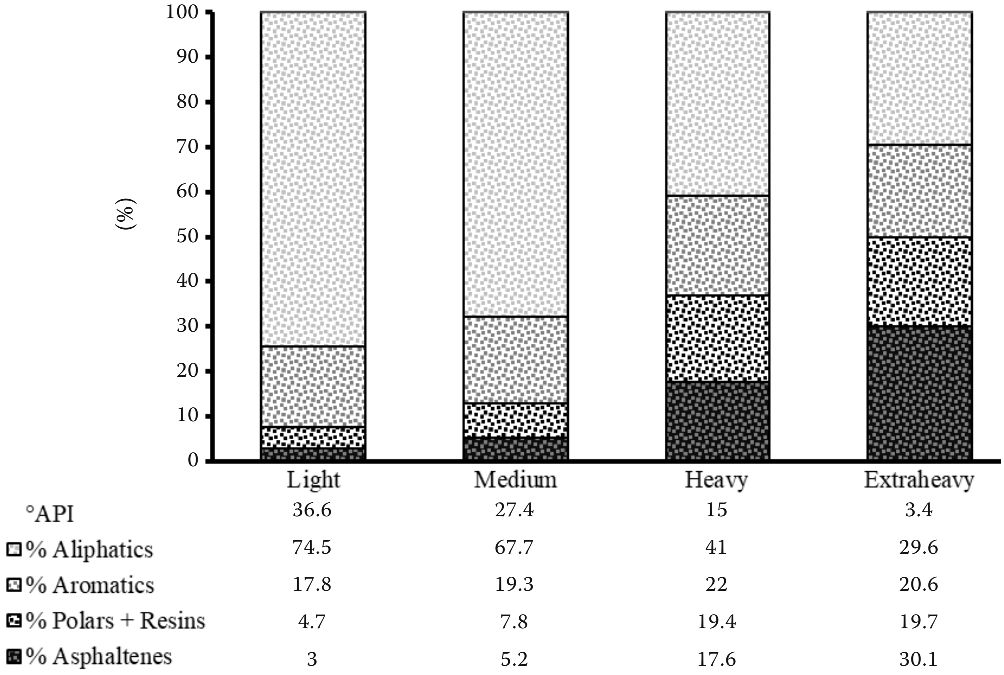

Figure 1. Composition of different crude oils according to chemical groups

common grasses used by ranchers in the area, and is adaptable to a variety of soils. It is well adapted to conditions of poor nutrition as well as extreme moisture and some seasonal drying (ACIAR-BIAC 2020). The cultivar used in this region was initially obtained from red clay soils in hilly areas of the northern part of South Africa, and it is naturally very well adapted to poor nutrition, with a fine, diffuse root system able to extract sufficient nutrients even from poor (or contaminated) soils (Zavala Cruz et al. 2005). It is the preferred pasture for many ranchers in the southeastern region of Mexico, especially for sandy soils, red clay soils, and many seasonally flooded soils, which represent the majority of soils in the region (Palma-López et al. 2017). Although some researchers have been quite successful in trying different pasture types for soil remediation (Zavala-Curz et al. 2005, Ruley et al. 2019, Wyszkowska et al. 2019, Orocio-Carrillo et al. 2024), this was beyond the scope of the present study, which was to evaluate crude oil impacts on pasture production using one of the most common types of pasture used by ranchers in the region. Furthermore, previous research using this grass in contaminated areas has been conducted locally with promising results (Rivera-Cruz and Trujillo-Narcia 2004, Zavala et al. 2005).

In some local areas, for example, in seasonally salt-stressed coastal soils or degraded, eroded soils, especially in uplands, or in some contaminated areas, ranchers are known to use a strain of Cynodon dactylon, locally known as Alicia grass or "grama". This is done when other grass species cannot be maintained. Alicia grass can grow under these stressful conditions because it has a much lower water and nutrient demand on the soil. It is possible that if this grass had been used in the present study, the contamination effects would not have been as pronounced. However, this species produces significantly

Table 2. American Petroleum Institute (API) gravity and sampling locations of the crude oils used in the study

°API	Classification	Source
3.4	extra-heavy (weathered)	Agua de Mina Dam, 15Q 315210E, 1975064N, Texistepec Mining Unit, Veracruz
15	heavy	Well No.1459, 15Q 308849E, 1980689N, Texistepec Mining Unit, Veracruz
27.4	medium	Oil well Tajón No.101, 15Q 475484E, 2038337N, Ejido Puerto Ceiba, Paraíso, Tabasco
36.6	light	Pipeline spill from Jujo No.52A, 15Q 488609E, 1990264N. R/a Cumuapa 3ra. Secc., Cunduacán, Tabasco

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less forage per hectare, and the forage produced is inferior in terms of nutrition, particularly in protein content (ACIAR-BIAC 2020a). The use of this species for forage is basically as a last resort for some ranchers.

Plants were collected in Pailebot, near the Arenosol sampling site. Collected from the roots, the plants were placed in plastic coolers, each containing ~5 L of water. These were covered with palm branches to prevent damage to the grass during transport. Grass was planted in the soil (three replicates/soil type) and allowed to grow under tropical conditions for two months, with relief irrigation for the first 15 days. After 30 days, the aerial biomass was cut to homogenise the treatments. After 30 days of regrowth, the crop biomass was quantified by cutting with scissors to a height of 7 cm above ground, simulating grazing. The cut biomass was placed in pre-weighed paper bags and reweighed. The samples were then oven dried (48 h, 60 °C). Dry weight was noted, and biomass was calculated by difference. Cuts were made monthly for six months. Primary production for pastures was calculated according to the average, considering the experimental unit diameter, converting to ton/(m^2 × year). Finally, dose-response curves were determined for each soil type as the percentage reduction in dry biomass production (compared to the uncontaminated control) *versus* oil concentration, using the trendline regression function in MS Office Excel, ver. 2013 (Microsoft Corporation, Redmon, USA).

RESULTS AND DISCUSSION

Pasture reduction *vs.* hydrocarbon concentration with heavy oil. In Figure 2, dose-response curves are presented for the reduction in biomass (with respect to the uncontaminated control) *versus* oil concentration for the Arenosol, Vertisol, and Gleysol, showing good agreement between the regression functions and the data (R^2 = 0.94–0.98). These are similar to the Freundlich adsorption isotherms, commonly observed in hydrocarbon-contaminated soils (Fu et al. 2021), and may be related to surface phenomena,

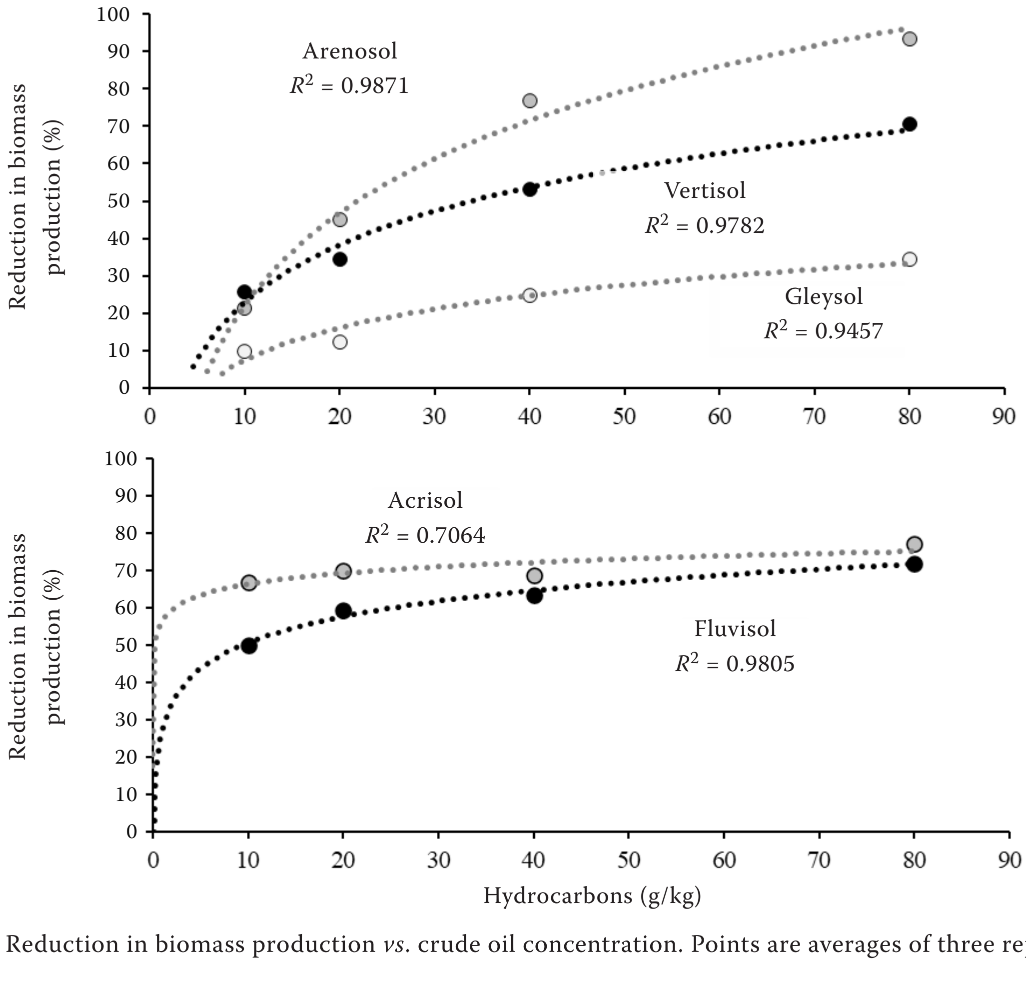

Figure 2. Reduction in biomass production *vs*. crude oil concentration. Points are averages of three replicates

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especially the formation of oily laminates on soil surfaces. As mentioned by Álvarez-Coronel et al. (2023), a higher oil concentration covers a greater portion of the soil surface. It may produce greater water repellency and/or a reduction in field capacity, leading to a pronounced decrease in pasture production. In sandy soils (like the Arenosol), this is probably the primary cause of fertility loss from oil contamination (Adams et al. 2016).

Notably, the reduction is significantly less in the Vertisol than in the Arenosol, presumably due to differences in soil texture. Vertisols have a high amount of smectites and therefore, much more external and internal surface area. More oil is needed to saturate the entire soil surface and cause water repellency, reduce field capacity, or interfere with nutrient availability. In the Gleysol, the impacts are even less. Both soils showed vertic properties in the field in the dry season (Gilgai microrelief or deep crevasses), and have similar levels of fines (Table 1). However, the Gleysol had a much greater amount of organic material (29% more), which may have further mitigated these kinds of impacts. According to the regression functions for these soils, to completely avoid pasture reduction, the heavy oil concentration would have to be reduced to about 0.4–0.6%. To have only slight impacts (conserve 90% of pasture production), the heavy oil concentration would need to be 0.71%, 0.56%, and 1.23% in the Arenosol, Vertisol, and Gleysol, respectively.

Although it is less common for petroleum hydrocarbon-affected soil to exhibit problems of nutrient availability than water repellency, the original studies by Roy and McGill (1998) found that some highly contaminated sites in Alberta did show a reduction in cation-exchange capacity (CEC). To date, research in SE Mexico has not found a reduction in CEC in very water-repellent soils (Alvarez-Coronel et al. 2023). Nonetheless, nutrient availability and water availability are both phenomena associated with soil surfaces, and the shape of the dose-response curves in the present study strongly suggests a surface phenomenon (or phenomena), especially in the Arenosol, Vertisol, and Gleysol. It is likely that in the Arenosol, water repellency would be more prevalent, while in the Vertisol and Gleysol, nutrient availability problems would be more pronounced, but mitigated by the higher retention of nutrients and organic matter, which can buffer the effects of hydrocarbons. Likewise, water stress on the microbial community can hinder the mineralisation of nitrogen and phosphorus from soil organic matter, and thus cause nutrient stress to the vegetation (Roy and McGill 1998). However, these same authors found "no consistent trend in the relative or absolute distribution of NH_4-N and NO_3-N forms in non-wettable and wettable soils". Nonetheless, some of the very early studies did show a reduction in extractable phosphorus and NO_3-N in crude oil-contaminated soil used for corn production (Udo and Feyemi 1975). Additionally, in at least one more recent study, diesel and petroleum contamination led to a decrease in available phosphorus and magnesium in the soil (Wyszkowska et al. 2015). And although Trujillo-Nájera et al. (2014) did recommend the addition of organic amendments to improve the nutrition of crude-oil-impacted soil, this was done on a Fluvisol that was already remediated by soil washing and chemical oxidation, and that had lost some SOM, probably due to the chemical oxidation treatment. From the data collected, a nutrient availability problem cannot be ruled out. Future studies should be designed to systematically test for these kinds of impacts (nutrient availability).

The impacts on soils with higher amounts of non-smectite fines were much more severe (Figure 2), increasing rapidly from 0% to 1% oil, while still showing Freunlich-type absorption curves. The reductions in pasture production at only 1% oil were 50% and 67% in the Fluvisol and Acrisol, respectively, compared to 21.4%, 25.8%, and 9.9% in the Arenosol, Vertisol, and Gleysol. This is most likely due to the kinds of fine particles in these soils. Although the silt and clay content of the Fluvisol was very similar to that of the Vertisol, the types of clays present were different; the Fluvisol did not exhibit the typical Gilgai microrelief or other vertic properties. Likely, in addition to smectites, the Fluvisol also contained significant quantities of non-shrink-swell clays (kaolinites, vermiculites or illites), and was thus more prone to compaction.

In the Acrisol, this was especially pronounced, most likely due to compaction from the kaolinites in this soil. Álvarez-Coronel et al. (2023) found that soils high in kaolinite were especially susceptible to compaction when contaminated with heavy oil. After this marked initial increase in pasture impacts, further reductions were significantly less, at 77.3% at 8% oil (similar to the Vertisol at 70.7%). The variability of this parameter was similar to that of the data sets from other soils; however, the change over the range of oil concentrations studied was significantly less (approximately 10%). This resulted in a similar regression function, however, with a lower variation coefficient (R^2 = 0.71 *vs.* 0.98 in the Fluvisol, Figure 2).

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A summary of these data is presented in Table 3. The TPH-caused impacts in the different soils appear to depend on the type and amounts of fines in the soil, as well as the hydrocarbon concentration. For those soils with practically null (Arenosol) or low quantities of non-smectite fines (Vertisol, Gleysol), the impacts at low concentrations of TPH are relatively low. As mentioned previously, these types of soil are not prone to compaction. Furthermore, numerous studies have demonstrated that sandy soils are particularly susceptible to water repellency, which is likely the case here. For the Vertisol and Gleysol, the causes are less clear. Still, they are probably due to reduced water or nutrient availability resulting from the formation of oily laminates on the soil surface, which is mitigated by the high surface area and organic matter content. In all three of these soils (Arenosol, Vertisol, Gleysol), the TPH concentrations that would still be protective of 90% of pasture production (according to these dose-response curves) were relatively high (Table 3).

Although the interpretations of the data are based on indirect evidence, they are congruent with and supported by the published scientific literature. Previous studies have indicated that the most common impacts to oil-contaminated sandy soils are from water repellency and a reduction in FC (Adams et al. 2016, Álvarez-Coronel et al. 2023). Likewise, it has been shown that impacts on clayey soils rich in smectites tend to be less and may be due to water stress under arid conditions, or obstruction of soil pores (waterlogging) under very moist conditions. However, one cannot rule out reduced nutrient availability (Udo and Feyemi 1975, Wyszkowska et al. 2015, Álvarez-Coronel et al. 2023). Furthermore, a recent study found that the type and amount of clay play a significant role in soil compaction, with soils high in non-smectite clay being especially susceptible (Álvarez-Coronel et al. 2023). In other fields of research, high silt contents in soils have been related to good compaction for construction purposes (Hasan et al. 2015), and it is probable that, in general, soils with relatively high amounts of non-smectite fines may suffer compaction. The soils practically without fines (Arenosols) do not suffer in this way, and the shrink-swell characteristics of soils high in smectites (Vertisols, many Gleysols) almost certainly mitigate or prevent this. In the construction field, before building on soils high in smectites, they are treated (usually by addition of calcium hydroxide) to prevent swelling and allow sufficient compaction for construction (Barman and Dash 2022).

Table 3. Summary of pasture yield reduction data with heavy crude oil

Soil type	Dose-response curve equation	R^2	TPH concentration (mg/kg) to conserve 90% of pasture yield	Observations				
				smectite clays	non-smectite fines	most probable causes of impacts		
						water repellency/ FC reduction	nutrient availability	compaction
Arenosol	$y = 35.676\ln(x) - 60.055$	0.987	7 100	nearly absent	nearly absent	×	–	–
Vertisol	$y = 22.171\ln(x) - 28.088$	0.978	5 600	abundant	low	×	×	–
Gleysol	$y = 12.471\ln(x) - 21.252$	0.946	12 300	abundant	low	×	×	–
Fluvisol	$y = 10.13\ln(x) + 27.386$	0.981	~ 200	low	abundant	×	×	×
Acrisol	$y = 4.2343\ln(x) + 56.655$	0.706	< 100	nearly absent	very abundant	–	–	×

[a]y – per cent reduction in pasture yield; x – TPH (total petroleum hydrocarbon) concentration, thousands; FC – field capacity

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The acceptable protective TPH levels (i.e. possible cleanup goals) for soils with low or null non-smectite fines are generally in the range of 0.5–1.5%. However, for the Arenosol and Vertisol, the protective levels are considerably lower than the 1% oil criterion proposed by the American Petroleum Institute for soil fertility. In sites where it is difficult to achieve these cleanup criteria, it may still be possible to restore soil fertility using regenerative agricultural methods and base site restoration goals on water repellency and/or field capacity, as compared to a nearby uncontaminated site.

In contrast, the soils with considerable amounts of non-smectite fines (silts, vermiculite, and illite in the Fluvisol, kaolinite and Al/Fe amorphics in the Acrisol) were much more susceptible to hydrocarbon-induced impacts to pasture production even at low TPH levels. It appears that this was caused by compaction, possibly in conjunction with water repellency or nutrient availability. For these soils, according to the dose-response curves, it would be necessary to reduce the TPH concentration to very low levels (<100–200 mg/kg) to preserve 90% of pasture production. These levels are far below the 1% oil criterion, and the technical possibility of actually achieving this in oil-spill-impacted soils is very questionable. It is probably technically impossible, or at least not economically feasible.

Under these conditions, it would be preferable to remediate to levels that are basically non-toxic to soil organisms, followed by site restoration to recover fertility. To ensure non-toxic conditions, it may be helpful to employ a bioassay comparing remediated soil with a nearby non-contaminated reference area (Wieczorek and Baran 2022). Likewise, relatively recent methods have been developed to quickly determine the toxicity of soil organisms (earthworms) in contact with soil (Jiménez et al. 2023). Upon achieving non-toxicity, soil restoration to overcome compaction (the most likely cause of the extreme impacts observed in the present study) could involve deep ploughing, organic amendment, and planting of a fine-rooted grass (Colonego et al. 2017, Colombi and Keller 2019). In humid-tropical conditions, a brief pasture foraging (preferably by bovine cattle) once a year could help stimulate growth. After two to three years, site conditions may be restored to background fertility levels, allowing for a robust soil biota. This could overcome the impacts of crude oil contamination without actually lowering the TPH concentration to (probably) impossibly low levels, but would be important especially for rural sites where agricultural productivity is of greater importance to landowners. In practical terms, the site remediation would need to be purposefully directed towards enhancing fertility as a cleanup goal. In some areas, it might be more practical legally first to use conventional methods to achieve cleanup norms (maximum permissible hydrocarbon concentrations), followed by site restoration based on soil fertility parameters, such as compaction, CEC, N/P availability, and water repellency/FC.

Relationship between crude oil type and biomass reduction at 1% oil. The results presented above illustrate the relationship between biomass reduction and oil concentration using a crude oil similar to that found at most contaminated sites in the region, many of which suffer from historical and chronic oil contamination, resulting in heavy and extra-heavy oil due to weathering in the tropical environment. The results show that for most regional soils contaminated with this type of oil, the cleanup criteria initially proposed by the American Petroleum Institute (1%) are inadequate to maintain reasonable levels of pasture production (90%), with a possible exception for Gleysols.

In addition to this evaluation, the applicability of the 1% oil cleanup criterion was also investigated for other kinds of crude oils (Table 4). For most treatments, the number of replicates (3) was insufficient to demonstrate a significant difference from the control. With only three replicates, it was difficult to confirm statistical differences, considering the variability and robustness of the response. It is probable that with more replicates, the differences could be shown to be statistically significant. Nonetheless, the tendencies were clear: at 1% oil, all treatments showed a reduction in pasture production between approximately. 20–65%, except the Gleysol. Furthermore, the magnitude of the reductions (averaging 35% to 65%, except for the Gleysol) strongly suggests that these tendencies are real. Future experiments should include a greater number of replicates to demonstrate this conclusively.

The highest average reductions were found in the Acrisol (55.9%) and the Fluvisol (53.9%). This is in agreement with the idea that some of the most significant impacts from petroleum hydrocarbons probably come from compaction in soils with large amounts of non-smectite fines. This was statistically significant for the Acrisol contaminated with heavy crude. Meanwhile, the average values for soils without large amounts of non-smectite fines (Arenosol, Vertisol and especially the Gleysol) were

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Table 4. Reduction in pasture production at 1% crude oil

Soil type	Pasture production (Tn/ha × year)									Average % reduction	% reduction, range
	uncontaminated control	light crude		medium crude		heavy crude		extra-heavy crude			
			% reduction		% reduction		% reduction		% reduction		
Arenosol	11.90^{a}	6.96^{a}	41.5	6.26^{a}	47.4	9.35^{a}	21.4	3.84^{b}	32.3	35.7	21.4–67.7
Vertisol	16.10^{a}	6.20^{a}	61.5	9.36^{a}	41.9	11.96^{a}	25.7	8.68^{a}	46.1	43.8	25.7–61.5
Gleysol	9.38^{a}	8.24^{a}	12.2	9.73^{a}	-3.7 (increase)	8.45^{a}	9.9	11.00^{a}	–17.2 (increase)	0.3	12.2% reduction to 17.2% increase
Fluvisol	16.71^{a}	7.44^{a}	55.5	5.68^{a}	66.0	8.44^{a}	49.5	9.25^{a}	44.6	53.9	44.6–66.0
Acrisol	12.87^{a}	4.66^{a}	63.8	8.37^{a}	35.0	4.24^{b}	67.1	5.43^{a}	57.8	55.9	35.0–67.1
Average % reduction			46.9		37.3		34.72		32.72	37.9	

[a]Superscripts refer to data sets that do not show a statistical difference within the same soil type

much lower: 35.7% and 43.8% for the Arenosol and Vertisol, respectively, and extremely low (0.3%) in the Gleysol. In the Gleysol, there were two cases (with medium and extra-heavy crude oil) that did not present a reduction in pasture production, but rather an increase.

This increase was modest (3.7%) in the medium crude oil-contaminated treatment but considerable (17.2%) in the extra-heavy crude oil-contaminated soil. This could be due not only to the high amount of smectites in this soil, but also to the high amount of organic matter, which could mitigate compaction problems.

Likewise, some authors (Álvarez-Coronel et al. 2023) have presented data suggesting that fine clays in marshy soils may agglomerate into larger, sand-size particles in the presence of heavy oil rich in asphaltenes, polars, and resins. This could have improved soil structure in this marshy soil and increased pasture production; however, this would need to be confirmed in future studies.

In summary, for all soils except the Gleysol, the 1% oil rule was insufficient, by itself, to maintain a minimum pasture production at a reasonable level (90%). Furthermore, probably, the original studies by Deuel (1991) commissioned by the American Petroleum Institute may have been skewed due to the high content of bentonite clay from the drilling cuttings incorporated into the soil at the study sites, thus the similarity in the original study (with bentonite incorporated into the soil), and the present study (with a montmorillonite rich Gleysol – both smectite clays). These data demonstrate that not only for heavy crude oil, but also for other crude oils (light, medium and extra-heavy), the 1% cleanup criterion is inadequate to protect pasture production in most regional soils, with the possible exception of some Gleysols.

It is worth noting that this study was conducted with one of the most prevalent forage grasses in the region. However, in fertile alluvial soils, some ranchers may use other forage grasses, such as *Cynodon nlemfuensis* (African Star grass), which can produce more forage per hectare and have a higher protein content per kilogram. However, these kinds of pastures can only achieve this in good, fertile soils that can meet their higher demand for water and nutrients (ACIAR-BIAC 2020b). It is probable that if this kind of species were used in this study, the impacts would be even greater, especially considering that oil contamination typically reduces water and nutrient availability in the soil.

This study was performed outdoors in southeast Mexico, in a tropical-humid environment. As such,

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it would be expected that other areas with petroleum production and similar climates (Southeast Asia, West Africa, the Amazon Basin, Venezuela, and Colombia) would yield comparable results. These results may also be extrapolated to humid subtropical regions with petroleum production, such as southeast Texas, Louisiana, southern Brazil, the Argentine Mesopotamia, Assam in India, and southern China (Brownfield et al. 2012). However, in drier areas such as northeastern Mexico, central and west Texas, Oklahoma, northeastern Brazil, Zulia in Venezuela, Gujarat in India, as well as parts of southern Russia and Kazakhstan, and the Canadian Prairie Provinces, the impacts caused by water stress (water repellency, reduced FC) would almost certainly be more pronounced (Minnikova et al. 2023, Nadeau et al. 2023). Likewise, under these drier conditions, the impacts caused by compaction could be greater. Similarly, impacts due to nutrient availability would also probably be more severe.

In Arctic and subarctic production areas (Alaska, Canada, Russia, Patagonia), it is doubtful that the results from the present study can be applied, as the temperature regimes and water availability are significantly different (Feddema 2005). Likewise, for production areas in extremely arid regions such as the Middle East, North Africa, and Western China (Nadeau et al. 2023).

With respect to soils, Histosols were excluded from this study since they are typically too flooded to be used even seasonally for pasture. We would expect that other, similar soils from Pliocene/Pleistocene terraces (such as Alisols, Luvisols, Lixisols, Ferrasols, Plintosols, etc.) would show comparable results to the Acrisol in the present investigation. However, some thin soils, especially from more arid regions, may show greater water and nutrient stress (WRB 2022).

Also, many soils formed under prairie/steppe (such as Chernozems, Kastanozems and Phaeozems) could be more resilient, especially if they have higher amounts of SOM produced from the humification of grass root exudates (WRB 2022). The SOM of these types of soils is notorious for enhancing various aspects of soil fertility, including reducing compaction, increasing CEC and thereby increasing available N and P, and increasing FC, thereby reducing water stress.

In these kinds of contrasting climates and in thinner, drier soils, or in rich mollic soils, similar studies would need to be conducted to determine the applicability of the 1% rule and define appropriate remediation or restoration criteria for site cleanup.

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