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- Science du Sol -

Densification des sols sableux sous culture mécanisée

Cas du Nord-Est Thaïlandais

Par
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Soutenue le 21 mars 2005, devant le jury composé de :

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A la mémoire de mon ami Jalal Thafi

Résumé :

L'augmentation constante de la population dans les zones tropicales provoque la mise en culture de sols marginaux et fragiles. Le tassement des sols est l'une des dégradations physiques les plus récurrentes dans les écosystèmes agricoles. Les sols sableux qui recouvrent une grande partie du Nord-Est Thaïlandais ont un potentiel agronomique réduit du fait de leurs propriétés chimiques et physiques. La présence d'un horizon dense et résistant à la pénétration situé à 20-40 cm a souvent été invoquée comme l'une des principales contraintes à l'agriculture dans la mesure où il réduit l'enracinement de la plupart des cultures.

L'objectif de la thèse était de caractériser la dégradation physique des sols sableux du Nord-Est Thaïlandais induite par l'agriculture mécanisée de ces dernières décennies, d'en déterminer l'origine et les principaux mécanismes et de proposer des voies de prévention et réhabilitation.

La première phase du travail a consisté à caractériser les propriétés physiques des sols sableux de la région en dissociant les caractéristiques héritées du matériau parental, de la pédogenèse et de la mise en culture afin de clarifier la notion de dégradation anthropique. Nous avons ainsi pu monter que les sols sableux de la région présentent une grande homogénéité en terme de constituants et de propriétés physiques. L'horizon dense et résistant mentionné est le résultat d'une profonde réorganisation de la phase solide, induite par la déforestation et la mise en culture des ces 40 dernières années ; sa présence est généralisée indépendamment du type de sol ou du système de culture.

La seconde phase du travail s'est concentrée sur les mécanismes pouvant conduire à la densification et aux fortes résistances à la pénétration observées. Nos résultats ont mis en évidence une sensibilité à l'effondrement sous de faibles pressions et à de faibles humidités. Cette sensibilité à l'effondrement est à mettre en relation avec les constituants et le travail du sol. Par ailleurs, la notion de pré-consolidation n'étant pas applicable à ces sols, le passage répété d'engins conduit à un tassement additif. Les propriétés physiques conduisent ces sols à de très fortes cohésions dès lors que l'arrangement des constituants est serré.

La dernière phase du travail a été focalisée sur la prévention et réhabilitation des sols dégradés. Considérant la sensibilité des sols, les techniques habituelles de labours profonds et sous-solages sont à proscrire. Des techniques alternatives qui visent à créer localement des zones de passage pour les racines tout en conservant la stabilité structurale de l'horizon sont conseillées. Deux techniques ont été étudiées : le rainurage qui correspond à un travail du sol localisé et la bio-perforation qui consiste en l'utilisation d'une espèce végétale dont les racines sont capables de créer des macropores dans la zone compacte.

Avant-propos :

Cette thèse a été réalisée dans le cadre d'une collaboration entre l'Institut National de Recherche Agronomique[1], l'Institut de Recherche pour le Développement[2] et le Land Development Department[3]. Ces recherches ont bénéficié d'une Allocation du Ministère de la Recherche et des Technologies et elles ont été conduites sous la tutelle du National Research Council of Thailand[4].

Les travaux s'inscrivent dans le cadre du programme d'étude des sols cultivés à fortes contraintes physico-chimiques des régions chaudes mené dans le Nord-est de la Thaïlande par l'unité de recherche Ariane (IRD-UR067)[5] devenue unité de recherche SOLUTIONS au 1er janvier 2005 (IRD-UR176). Le principal objectif scientifique de la thèse est de fournir des éléments de réponses quant à l'évolution des sols sableux sous culture mécanisée.

La thèse est rédigée de manière à satisfaire deux objectifs : mettre à la disposition du lecteur un document synthétique qui reprend l'ensemble des travaux, et valoriser le travail de recherche sous forme d'articles dans des revues internationales.

La synthèse est rédigée en français et fait référence aux articles regroupés en annexes, chacun d'entre eux se focalisant sur un aspect de l'étude. Les articles sont rédigés en anglais au format de publication internationale. Afin de faciliter la lecture, chaque article contient un résumé en français et une liste indépendante de figures et de références.

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Introduction

Le sol fait partie intégrante de la plupart des écosystèmes terrestres et remplit une fonction fondamentale pour l'alimentation des communautés humaines. La dégradation des sols est par conséquent un problème environnemental d'une importance cruciale pour toutes les sociétés. Cette dégradation est souvent définie comme un phénomène anthropique qui diminue la capacité présente et/ou future du sol à servir de support à la vie humaine. Bien que le problème existe depuis les débuts de l'agriculture, son extension et son impact sont aujourd'hui à leur paroxysme (Lal et Stewart, 1990). Par ailleurs, l'augmentation constante de la population dans les zones tropicales provoque la mise en culture de sols marginaux et fragiles. Des sols ont été sévèrement dégradés dans la plupart des régions du monde, mais c'est dans les pays dont le revenu est le plus tributaire de l'agriculture que les conséquences économiques en sont les plus graves (Oldeman *et al.*, 1991).

La détérioration physique est l'une des trois principales composantes de la dégradation des sols (Figure 1). Cette détérioration, qui inclut des phénomènes tels que la densification, le tassement, l'érosion, ou encore l'induration, est en effet l'une des dégradations anthropiques les plus récurrentes dans les écosystèmes agricoles. Les différentes formes de dégradation physique des sols ont fait l'objet de nombreuses études ces dernières décennies. Plus particulièrement, le tassement des sols apparaît comme l'une des contraintes majeures de l'agriculture moderne (Soane et van Ouwerkerk, 1994; Hamza et Anderson, 2005). Le tassement des sols et les fortes densités qui en résultent sont le plus souvent attribués à l'utilisation de matériels lourds, en particulier à leur passage répété à une humidité au champ favorable à la déformation du matériau (Flowers et Lal, 1998).

Les sols sableux, bien qu'ils aient pendant longtemps été considérés comme structurellement inertes du fait de leur squelette rigide et de leur structure massive, n'échappent pas aux phénomènes de dégradation physique (Hartmann, 1991; Lamotte, 1995; Bortoluzzi, 2003). Cependant le comportement au champ de tels matériaux est encore mal connu, notamment du fait que le tassement est peu relié au poids des engins. Des questions subsistent quant à l'origine de la densification et à la relation entre porosité et résistance à la pénétration (Stock *et al.*, 2004). Certains travaux suggèrent l'importance du squelette (Chretien, 1986) et des relations squelette-plasma (Bruand *et al.*, 1997). D'autres auteurs se sont également tournés vers la physique des milieux granulaires pour expliquer les comportements de tels matériaux (Hartmann *et al.*, 2002).

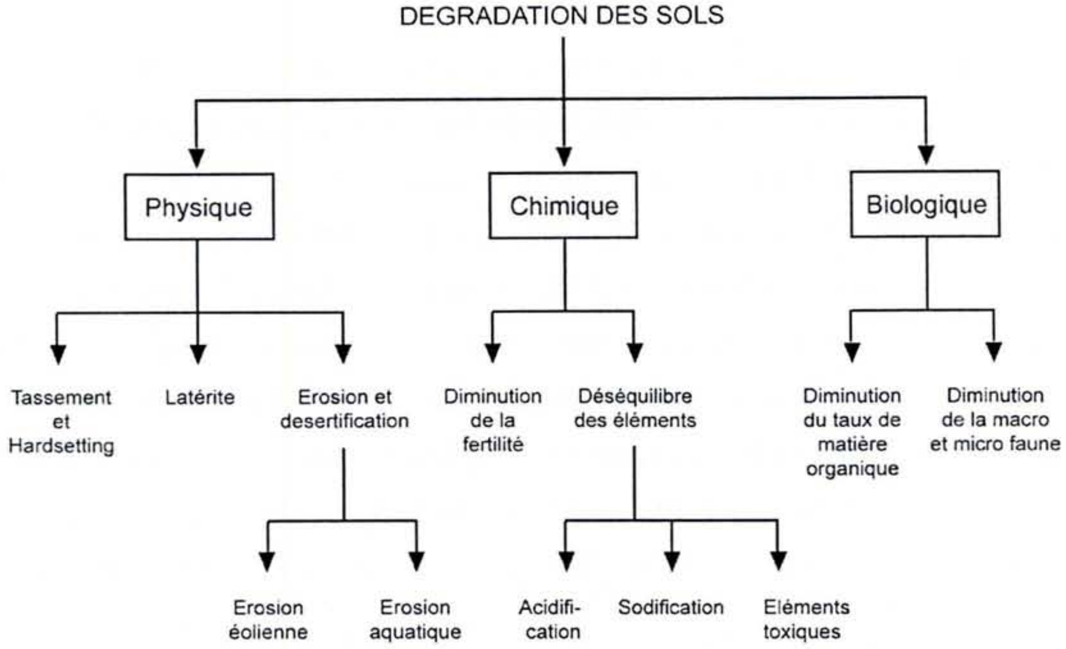

Figure 1 : Types et processus de dégradation des sols d'après Lal et Stewart (1990)

Les sols sableux sont répandus de par le monde, et plus particulièrement dans les zones tropicales où ils constituent un important enjeu économique malgré leur inhérente faible fertilité chimique (FAO, 1975). Ces sols occupent la majeure partie du Nord-Est Thaïlandais (Ragland et Boonpuckdee, 1987) qui constitue une remarquable unité naturelle de près de 170.000 km² abritant près d'un tiers de la population de pays. Dans cette région, la population a une densité proche de la moyenne nationale (110 hab./km²) mais elle doit faire face à un milieu physique particulièrement défavorable.

La végétation primaire était principalement constituée de forêts claires (*Dipterocarp)* jusqu'à l'intensive déforestation qui a débuté dans les années 60. Ces forêts claires qui supportaient une agriculture extensive ont alors laissé place, en majorité, à l'agriculture intensive des cultures de rente. Dès lors, les sols sont devenus problématiques et leur fertilité a décru rapidement (Kheoruenromne *et al.*, 1998). Les propriétés physico-chimiques (acidité, faible capacité d'échange cationique, faible taux de matière organique, peu de nutriments...) constituent en effet de fortes contraintes pour l'agriculture, mais elles n'expliquent pas entièrement les faibles rendements. Il a été montré que la dégradation physique, et plus particulièrement la présence d'un horizon plus dense et/ou plus résistant à la pénétration des racines et au travail du sol, constitue également une contrainte majeure à la production végétale (Hartmann *et al.*, 1999).

L'objectif de la thèse est double. J'ai principalement cherché à caractériser la dégradation physique des sols sableux du Nord-Est thaïlandais induite par l'agriculture mécanisée de ces dernières décennies, à en déterminer l'origine et les principaux mécanismes. J'ai également cherché à définir les voies possibles de prévention et de réhabilitation des sols densifiés.

Etudier la dégradation des sols induite par la mise en culture implique la connaissance précise d'un état initial non dégradé. La première phase du travail a donc consisté à étudier le matériau parental, les processus pédogénétiques qui ont conduit à la formation des sols, et l'impact de la mise en culture. Ce travail avait pour objectifs d'une part d'isoler les modifications induites par la mise en culture, d'autre part de déterminer un certain nombre de caractères communs aux sols de la région afin de permettre l'extrapolation des résultats. La seconde phase de l'étude s'est focalisée sur les mécanismes responsables de la densification et de l'induration observée dans les sols. Une attention particulière a été portée aux relations entre constituants et mécanismes d'évolution dans le souci d'exploiter ces résultats au-delà du contexte thaïlandais. Enfin, dans une troisième phase de l'étude, des méthodes de prévention et de réhabilitation des zones dégradées sont discutées. Deux techniques, jugées adaptables au contexte agro-économique du Nord-Est thaïlandais, ont été testées en station expérimentale.

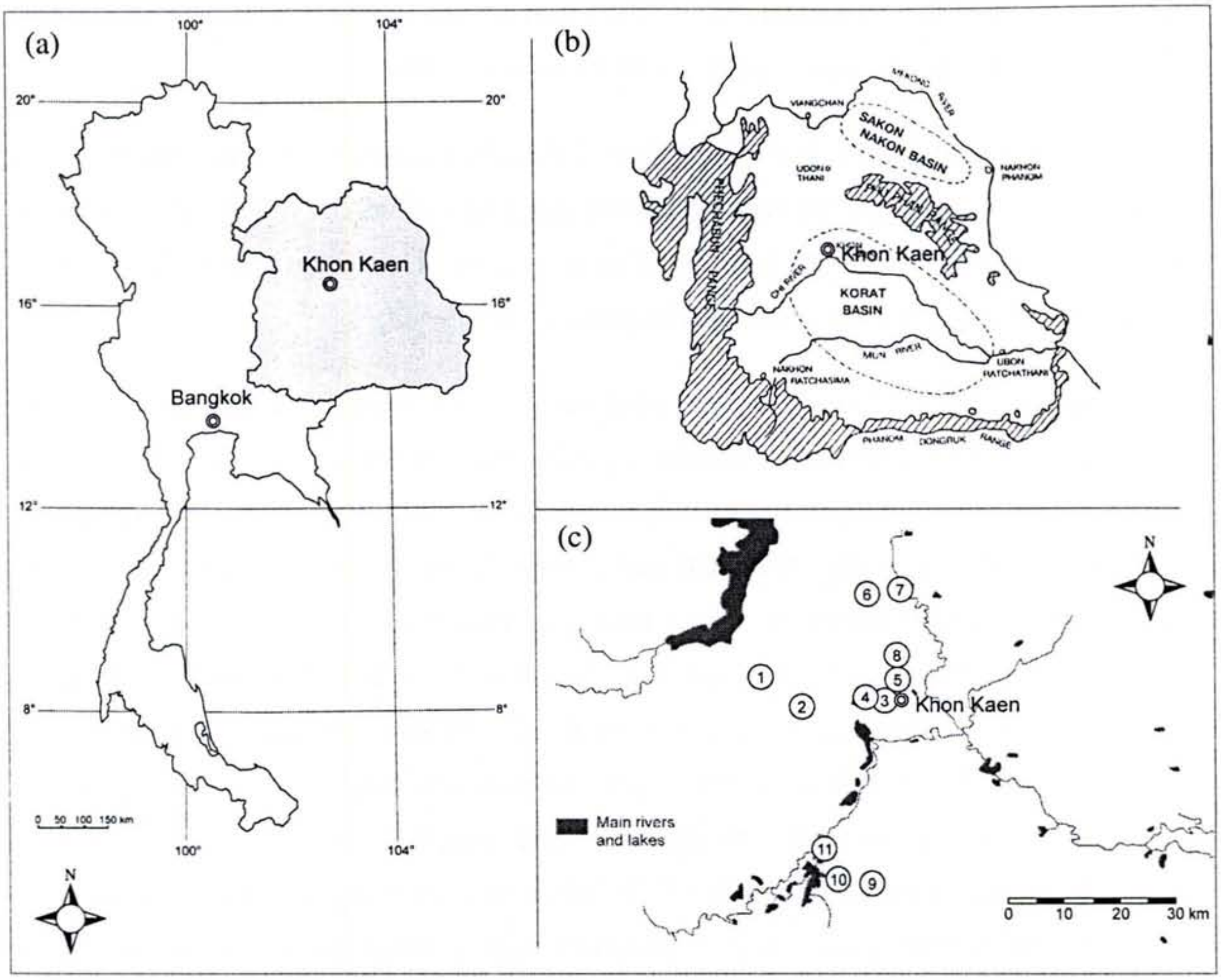

Figure 2 : Situation géographique (a) et physiographique (b) du Nord-Est Thaïlandais et position des sites d'étude (c)

Millions d'années	Ere	Période	Groupe	Formation
1,8	Cénozoïque	Quaternaire		Dépôts de sables Graviers
65		Tertiaire		Phutok : Grès Siltite Argilite
135	Mésozoïque	Crétacé	KORAT	Maha Sarakham Khok Kruat Phu Phan
195		Jurassique		Sao Kua Phra Wihan Phu Kraduang
250		Trias		Nam Phong Huai Hin Lat

Figure 3 : Stratigraphie géologique du Nord-Est Thaïlandais

Du matériau parental au sol actuel

Origine du matériau

Milieu physique et géologie

Le Nord-Est de la Thaïlande, également appelé Isaan, constitue une unité naturelle délimitée au nord et à l'est par le Mékong, à l'ouest par la chaîne de Petchabun et au sud par la chaîne Phanom Dongruk (Figure 2). La région se présente principalement sous la forme d'un plateau peu accidenté avec des collines basses, de larges vallées et des plaines faiblement ondulées. Ce plateau, communément appelé plateau de Korat, est séparé en deux bassins par la chaîne Phu Phan : au nord le bassin de Sakon Nakhon et au sud, le bassin de Korat. La région est donc composée de trois grandes unités géographiques : montagnes (13%), plateau (63%) et plaines inondées (7%).

La plus grande partie de la région est constituée par un ensemble de formation du Secondaire (65 à 250 millions d'années) appelé groupe de Korat qui comprend 8 formations (Figure 3). La formation de Maha Sarakham (Gardner *et al.*, 1967), qui est la plus récente et la plus importante du groupe de Korat, s'étend largement sous les deux bassins entre 356 et 610 m de profondeur (Vimuktanandana, 1985). Le Tertiaire (formations de Phutok) est constitué de grès, siltite et argilites. L'ensemble du Quaternaire est constitué de dépôts de graviers et de sables en surface.

L'une des principales caractéristiques de la région est la présence d'une couverture sableuse épaisse et uniforme attribuée au Quaternaire. Cette formation, souvent appelée *cover layer*, recouvre la quasi-totalité de la région et peut atteindre plus de 5 m de puissance. Ce manteau sableux est également mentionné au Vietnam, Cambodge, Myanmar, et dans les *Uplands* de Malaisie (Hoang Ngoc, 1989; 1994).

Débat sur l'origine des dépôts quaternaires

Si la présence généralisée de cette formation sableuse du Quaternaire fait l'unanimité dans la littérature, son origine reste controversée. Les travaux les plus souvent cités sont ceux de Moormann *et al.* (1964) qui attribuent les formations du Quaternaire à des dépôts alluviaux incluant graviers et sables. Ces auteurs se basent sur un modèle géomorphologique suggérant que ces formations constituent des terrasses alluviales façonnées par le fleuve Mékong et ses affluents. Ils reconnaissent trois niveaux de terrasses appelés *hautes, moyennes* et *basses terrasses*. Ces niveaux de terrasses s'étendent aux deux grands bassins du Nord-Est, respectivement de Korat et de Sakon Nakhon (Figure 2).

L'hypothèse d'une origine fluviale unique des dépôts Quaternaires a cependant été fortement contestée. Ainsi, plusieurs auteurs ont remis en cause l'origine fluviatile de ces terrasses (Michael, 1982; Boonsener, 1983; Löffler *et al.*, 1984; Pramojanee *et al.*, 1985; Dheeradilik et Chaimanee, 1986; Tamura, 1992). Considérant la géomorphologie et la granulométrie des sables, Boonsenner a remarqué en 1983 que la couverture sableuse présente une organisation et un grano-classement typiques des dépôts éoliens. Hoang Ngoc (1989; 1994), Sibrava (1993) et Sibrava et Shimanovich (1994) ont également développé une hypothèse similaire au Vietnam et en Thaïlande. Pramojanee *et al.* (1985) ont cependant montré que la granulométrie du présumé dépôt éolien était identique à celle des grès et des conglomérats des formations de Maha Sarakham et Khok Kruat et ont suggéré une altération *in-situ*. Löffler et Kubiniok (1996) considèrent quant à eux que la couche de sable n'est ni un dépôt fluviatile ni un dépôt éolien mais un remaniement sur place effectué par bioturbation. Cette hypothèse suppose en particulier la remontée de particules fines par les termites. Plus récemment, Sanderson *et al.* (2001) ont utilisé la luminescence pour argumenter l'hypothèse de dépôts éoliens. Cette méthode leur a permis de prouver que les quartz de la couverture sableuse sont d'âge différent de ceux de l'horizon sous-jacent. L'origine même et le mode de transport restaient cependant indéterminés.

A ce stade il était donc important d'obtenir des arguments sur le type d'apport, éolien ou fluvial. L'intérêt pour cette thèse était de discuter des propriétés associées au dépôt, en particulier son homogénéité, ses propriétés physiques et ses propriétés mécaniques.

La preuve d'une origine éolienne des dépôts

Lorsqu'une roche est soumise à l'altération elle libère une fraction de ses minéraux constitutifs sous forme de grains. Ces grains peuvent ensuite être transportés par la glace, le vent, les rivières ou la mer. Ils sont parfois piégés et soumis aux influences pédogéniques et dans certains cas peuvent être libérés à nouveau et entraînés plus loin. En ce qui concerne des matériaux peu altérables comme les quartz, les grains subissent progressivement au cours de leurs tribulations des modifications plus ou moins importantes de taille, de forme et d'aspect par rapport aux caractères originaux qu'ils avaient au sein de la roche-mère dont ils sont issus. Les grains qui se trouvent dans les formations sédimentaires portent à leur surface le témoignage de leur histoire. Il s'agit d'une multitude de traces héritées des diverses influences auxquelles ils ont été soumis au cours de leur long voyage : ces traces constituent un véritable curriculum vitae dont la lecture apporte des renseignements sur leurs conditions de transport et d'évolution (Le Ribault, 1977).

Sur ces bases, nous avons réalisé une étude complète des quartz de plusieurs formations sédimentaires et sols de la région de Khon Kaen (Annexe 1) en utilisant l'approche micromorphogénique. L'approche micromorphogénique (Prone, 2003) combine quatre niveaux d'analyse (granulométrique, morphoscopique, exoscopique et endoscopique). Notre objectif a été de mettre en évidence des critères micro-texturaux qui rendent compte du mode de transport des matériaux. Ceci nous a permis d'avancer dans la connaissance de l'origine et du mode de dépôt.

En premier lieu, nous avons montré que les tous les échantillons prélevés dans la couverture sableuse possèdent une répartition des classes granulométriques des grains de sables très similaire (mode à 125 µm). Nous avons également mis en évidence la présence de grains de quartz Ronds Mats et Non Usés Evolués dominants ainsi que de nombreuses traces d'impacts (cupules, croissants et V de choc). Ces caractères sont typiques de matériaux transportés par le vent et ils prouvent l'origine éolienne de haute énergie des dépôts Quaternaires étudiés.

Une étude plus détaillée a mis en évidence des stries de frottement et des traces de broyage indiquant un épisode périglaciaire antérieur. En outre la présence de quartz rhyolitiques automorphes inconnus dans les roches encaissantes de la région, indique que ces matériaux n'ont pas évolué sur place. Cet ensemble cohérent de résultats montre que tous les matériaux Quaternaires et les sols étudiés sont dérivés de sables éoliens. Si l'on tient compte de la géographie, ces matériaux ont probablement été transportés depuis les contreforts de l'Himalaya au nord du Laos ou du Vietnam ou encore depuis la Chine du Sud.

Dès lors que les matériaux apparaissaient très homogènes au plan granulométrique, nous avons réalisé une étude systématique des sables sur 10 profils de sols répartis sur deux séquences représentatives de ce que les géologues ont appelé basse et de moyenne terrasse. Les résultats présentés en Annexe 2 rendent compte de l'étonnante homogénéité des sables constituant les sols de la région. La séquence de moyenne terrasse présente des sables légèrement plus grossiers, mais le mode reste centré à 125 µm de diamètre pour tous les profils étudiés, indépendamment de la profondeur (0-100 cm). Nous avons ainsi confirmation que l'hypothèse éolienne est la seule pertinente pour expliquer l'origine des substrats sableux.

Conclusions

L'homogénéité du squelette sableux, l'absence de stratification, la finesse des grains de sable, l'abondance des limons et les propriétés exoscopiques des quartz nous indiquent que les sables Quaternaires de la région se sont développés dans un matériau d'origine lointaine apporté par le vent pendant une période glaciaire. Ces dépôts sont de puissance très variable : s'ils atteignent plus de 7 m dans certaines zones, ils ne représentent que quelques dizaines de centimètre en d'autres points. La carte géologique (Vimuktanandana, 1985), basée sur les niveaux de terrasses ne rend pas compte de cette homogénéité de la couverture sableuse dans laquelle les sols de la région se sont développés, dans la mesure ou la roche cartographiée est parfois sous-jacente à la couverture sableuse. De nombreux profils stratigraphiques des dépôts Quaternaires ont été proposés (Boonsener, 1991), se heurtant souvent aux conflits d'origine du matériau et de variabilité des puissances dans le paysage. Dans la mesure où notre étude se focalise sur les sols, nous avons adopté la stratigraphie simplifiée présentée en Figure 4. Cette stratigraphie adaptée de Mitsuchi *et al.* (1986) se compose des différents dépôts du Quaternaire sus-jacent à la formation de Maha Sarakham. Elle a l'avantage de bien rendre compte de la réalité de terrain que nous avons observée. La puissance de l'horizon de graviers, sans nul doute d'origine alluviale, est variable tout autant que celle des sables qui s'y superposent, et peut même être réduite à zéro dans certains cas. Nous considérerons ainsi que la couverture sableuse est homogène, généralisée et d'origine éolienne.

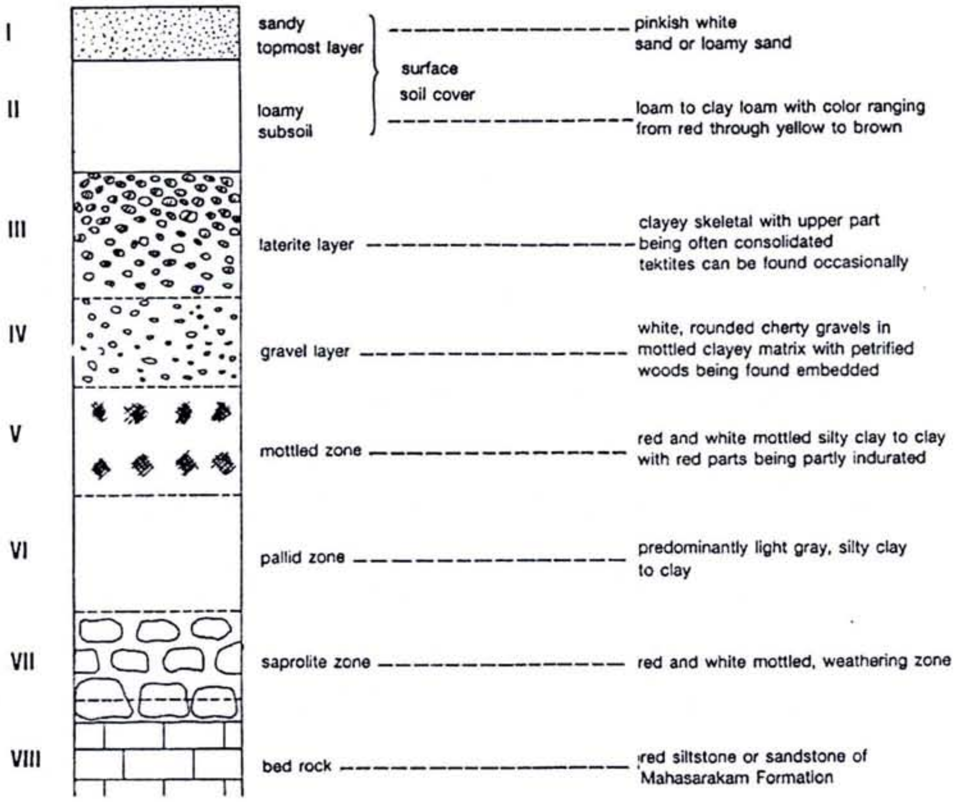

Figure 4 : Stratigraphie Tertiaire et Quaternaire du Nord-Est Thaïlandais

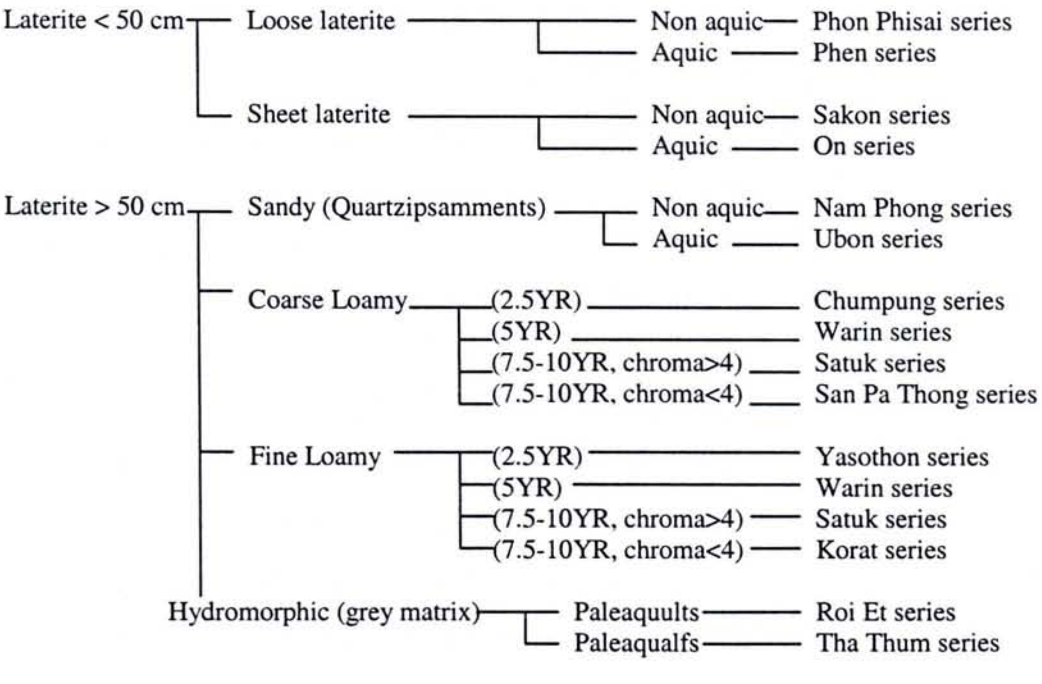

Figure 5 : Organisation et classification des sols dans le Nord-Est Thaïlandais

Classification des sols et pédogenèse

Classification des sols

Les sols de la région ont été décrits et cartographiés en utilisant un système basé, d'une part sur les niveaux de terrasses introduits par Moormann et Rojanasoonthan (1972), et d'autre part sur la Soil Taxonomy (Imsamut et Boonsompoppan, 1999). La carte des sols à l'échelle 1:100.000$^{\text{ème}}$ couvre l'ensemble de la région et compte quelque 40 types de sols différents. La carte de sols apparaît très morcelée malgré l'homogénéité du matériau que nous avons décrite précédemment. La définition de chaque série dépend à la fois de la texture, de la couleur dominante, de la profondeur et du régime hydrique (Figure 5). La répartition des sols est peu organisée dans le paysage et le grand nombre de séries de sols morcelées sur la carte rend la généralisation des études difficile.

Pour comprendre cette hétérogénéité, il est intéressant de revenir sur l'historique de la cartographie des sols. Pendleton et Sarot (1963) ont d'abord classé les sols non engorgés du plateau comme *Korat series*. Les sols engorgés ont, quant à eux, été classifiés de manière indépendante comme *Roi-et series*. Les re-classifications successives et divisions en nouvelles séries, en fonction de la texture, de leur couleur, et d'horizon témoins inspirés de la Soil Taxonomy ont conduit à établir une véritable mosaïque de sols qui ne reflète pas toujours les liens génétiques qui les rapprochent.

Les propriétés physiques des sols

Il nous est apparu intéressant d'essayer d'appréhender les sols dans un contexte moins contraint par leur classification. Nous avons choisi de faire ressortir l'homogénéité du matériau parental et les propriétés communes à ces sols sableux en mettant l'accent sur les similitudes et les disparités des sols à l'échelle du paysage. Nous avons ainsi étudié deux séquences des sols, initialement cartographiées comme basse et moyenne terrasse (Annexe 2). Pour chaque séquence, 5 profils ont été caractérisés. La granulométrie des sables, très homogène à l'intérieur des séquences (Annexe 2, Figure 5) est apparue indépendante du type de sol, des horizons et même de la position topographique. La distribution est légèrement différente entre les deux séquences mais reste centrée sur 125 µm, nous pouvons en conclure que les sols présentent une remarquable homogénéité granulométrique de la fraction sableuse, c'est à dire de leur squelette. En revanche, la teneur en fraction argileuse est très variable. Elle marque la différenciation des horizons et par conséquent des types de sol. Si l'on se réfère à la répartition de l'argile dans le profil, on observe une tendance générale à l'accumulation d'argile en profondeur (Annexe 2, Profiles). Ce phénomène peut être interprété en terme de lessivage, ce qui est en accord avec les classes de sols présentes sur la carte (Imsamut et Boonsompoppan, 1999) et les travaux concernant la mobilité des argiles (Boivin *et al.*, 2004). D'après nos résultats, une différenciation texturale due au lessivage existe de haut en bas du profil mais l'intensité du phénomène est variable d'un sol à l'autre, ce qui induit une limite plus ou moins nette entre un horizon de départ (E) et un horizon d'accumulation (Bt). Les transferts peuvent avoir lieu de façon transversale également, ce qui tendrait à expliquer l'augmentation du taux d'argile en bas de séquence (Annexe 2, Profiles L5-M5). On notera cependant que l'ensemble des horizons observés présente des textures très proches, en se répartissant dans les classes sableuse à sablo-argileuse (Annexe 2, Figure 3).

Les constituants

En ce qui concerne les constituants, la fraction sableuse et limoneuse est exclusivement constituée de quartz. Les grains sont transparents et contiennent de nombreuses inclusions ferrugineuses qui leur donnent leur couleur caractéristique (Annexe 2, Table 1). En fonction de la fréquence de ces inclusions, et de la présence de petits nodules couleur rouille, les couleurs des sables vont du blanc au rouge. Les grains sont un mélange de quartz émoussés et anguleux avec une tendance à l'angularité des petits grains. Les grains les plus gros présentent systématiquement de larges fractures qui rendent compte de l'énergie des chocs qu'ils ont subis lors de leur transport. La fraction argileuse est, quant à elle, constituée majoritairement de kaolinite avec une proportion importante de petits grains de quartz et quelques traces de minéraux argileux 2 :1. L'observation des quartz <2 µm contenus dans la fraction argileuse a révélé leur singulière angularité qui suggère qu'ils sont issus du fractionnement des grains les plus gros. On notera que les argiles sont des argiles de basse activité et de type non gonflant, ce qui explique la faible CEC des sols (Imsamut et Boonsompoppan, 1999), l'absence de structuration due au retrait-gonflement (Tessier, 1984), et l'induration à l'état sec (Mullins *et al.*, 1990).

Il apparaît *in fine* que les propriétés physiques des sols sont indépendantes de la classe de sol telle que cartographiée dans le système de classification de la Soil Taxonomy. En outre, la teneur en argile et sa qualité (à condition qu'elle varie suffisamment) peuvent être des paramètres importants du comportement physique des sols.

Evolution suite à la mise en culture

Une déforestation récente (30-50 ans)

La mise en valeur systématique des sols est récente puisqu'elle date des années 1950 à 1970. A l'issue de la déforestation effrénée qui a marqué les dernières décennies, peu de zones naturelles subsistent dans la région. De plus, les zones qui n'ont pas été défrichées correspondent souvent à des zones marginales comme les sols squelettiques développés sur les reliefs car leur potentialité au plan agronomique est faible. On notera par ailleurs que les profils de référence de la classification thaïlandaise ont pour la plupart été décrits dans des zones déjà cultivées (Imsamut et Boonsompoppan, 1999). Subsistent cependant quelques zones de forêt qui n'ont jamais été cultivées de façon mécanisée et intensive pour des raisons religieuse ou communautaire.

Une étude comparative des propriétés physico-chimiques entre des zones cultivées intensives et des zones de référence a été conduite par Noble *et al.* (2000), avec une attention particulière portée au phénomène d'acidification. Cette étude a révélé que, dans le Nord-Est thaïlandais comme dans d'autres zones tropicales, la mise en culture intensive s'est traduite par une acidification du profil et une diminution marquée de la fertilité des sols. En revanche l'évolution des propriétés physiques des sols est beaucoup moins documentée. La présence d'un horizon compact à faible profondeur est mentionnée dans de nombreux rapports et elle est en général interprétée comme une dégradation due à la mise en culture (Mitsuchi *et al.*, 1986). Cependant, en l'absence d'éléments comparatifs, il aurait été hasardeux d'attribuer le tassement à un mécanisme anthropique, dans la mesure où certains sols présentent des horizons denses à l'état naturel, i.e. analogues à ceux de Fragipans (Bruand *et al.*, 1997; Assallay *et al.*, 1998). De fait, la comparaison avec les zones cultivées intensives nous a paru prometteuse pour clarifier l'impact physique de la mise en culture.

Comparaison de couples forêt-culture

Afin de clarifier la notion de dégradation induite par la mise en culture, nous avons conduit une étude comparative de couples forêt-culture (Annexe 3). Trois sites ont été sélectionnés dans sur les critères suivants : i) la zone de forêt y était préservée ; ii) la zone de culture présentait un horizon dense et résistant à la pénétration ; iii) la limite forêt-culture était nette et brutale.

L'étude a montré que la mise en culture conduit à une intense densification des 50 premiers centimètres du profil indépendamment du type de sol, avec l'apparition d'un horizon à densité maximale entre 20 et 40 cm environ (Annexe 3, Figure 1). La variation de densité apparente correspond à un effondrement de plusieurs centimètres du sol par rapport aux zones non compactes. Nous avons montré par ailleurs que la densification se traduit par une très forte augmentation de la résistance à la pénétration à l'état humide comme à l'état sec.

L'approche micro-morphologique et particulièrement l'analyse d'image, a permis de caractériser les conséquences de cette densification sur l'organisation porale. Dans la zone cultivée la macroporosité d'origine biologique a complètement disparu, et la nouvelle organisation très serrée des constituants présente une porosité très fine et tortueuse. Cet assemblage, considéré par Bruand *et al.* (2004) comme responsable de la forte résistance à la pénétration d'un sol similaire de la région, est le résultat de la mise en culture.

La densification et l'induration mises en évidence par la comparaison des couples forêt-culture est similaire dans l'ensemble des sols cultivés que nous avons étudiés (Annexe 2). Cette dégradation physique, que l'on sait maintenant être reliée à la mise en culture, est indépendante du type de sol, de la culture et de la position topographique. L'ensemble des sols cultivés qui ont été étudiés se caractérise par la présence d'un horizon dense et résistant à la pénétration à faible profondeur.

Conclusions

Il ressort de ce qui précède que la densification est le résultat de la mise en culture et qu'elle affecte le sol à une profondeur de l'ordre de 50 cm. A ce stade de la discussion il est maintenant important de savoir comment la porosité diminue, en particulier de déterminer le rôle des facteurs biotiques et abiotiques susceptibles de modifier le mode d'assemblage des constituants et la résistance à la pénétration.

Mécanismes d'évolution des sols

Travail du sol et déstructuration

Les travaux liés à la déforestation et à la première mise en culture constituent la première étape du processus d'évolution des sols sous l'action de l'Homme. Les sols, initialement organisés dans une structure massive mais fortement aérée présentent des densités apparentes relativement élevées pour des sols sous forêt (environ 1.5 Mg.m^{-3}). Cependant, la présence d'une abondante macroporosité biologique interconnectée les rend faiblement résistants à la pénétration (Annexe 3). Mis à part les phénomènes de hardsetting lorsque le sol s'assèche, il existe suffisamment d'espace libre entre les constituants pour permettre le réarrangement nécessaire à la pénétration d'une racine ou d'un outil. On notera également que dans ce système l'activité biologique est suffisamment importante pour maintenir et renouveler cette porosité biologique.

Lorsque le sol est travaillé, la structure massive poreuse décrite précédemment explose en un arrangement d'agrégats relativement petits et sables déliés. Cet arrangement, qui est particulièrement visible à la surface des sols fraîchement labourés, présente lui-aussi une forte porosité. Il constitue une organisation métastable où la porosité biologique initiale a laissé place à une porosité plus fine délimitée par l'assemblage de ces agrégats et sables libres. Il est probable que ce matériau se comporte d'une manière similaire à un matériau granulaire à l'état sec. La répartition des forces selon les points de contacts et les phénomènes d'arches pourrait alors contribuer à la porosité (Duran *et al.*, 1998; Hartmann *et al.*, 2002).

Cette première étape ne constitue pas en elle-même une véritable densification, et les densités apparentes mesurées dans les horizons fraîchement labourés ne rendent pas bien compte de l'évolution porale et structurale induite par le travail du sol. La résistance à la pénétration est souvent plus faible que sous forêt dans la mesure où la structure n'est plus continue. Ainsi le travail du sol présente dans un premier temps l'effet ameublissant recherché. Cependant cette évolution structurale, très visible à l'échelle macroscopique, constitue un changement radical dans les propriétés physiques du matériau. D'une structure massive où la macroporosité est solidement encaissée dans un matériau stable, on passe à une structure métastable où la macroporosité se résume aux espaces inter-agrégats et inter-grains. Dans ces conditions, l'hypothèse est que la stabilité de l'ensemble et la porosité associée ne tiennent alors qu'au réseau de forces de friction entre agrégats qui maintient le système métastable en place.

L'étude de sols cultivés (Annexe 2) et des couples forêt-culture (Annexe 3) nous conduit à penser, au vu des pratiques culturales, que la profondeur maximale de l'horizon compact correspond approximativement à la profondeur maximale du travail du sol. Cependant les itinéraires culturaux sont très variables d'une exploitation à l'autre et dépendent en particulier des moyens techniques et financiers de l'agriculteur. Ces travaux profond sont mis en œuvre de manière occasionnelle tandis que le travail superficiel du sol à l'aide de la charrue à disques est très fréquent. Ce dernier permet l'ameublissement du sol, le sarclage ou encore la limitation de l'assèchement du profil en rompant le lien capillaire avec la surface. Dans ces conditions, il n'est pas étonnant que la limite inférieure de l'horizon travaillé (Ap) apparaisse clairement à seulement 15 cm de profondeur alors que le sol a été travaillé bien plus profondément certaines années. L'horizon sous-jacent, qui représente à lui seul la majeure partie du phénomène de densification, est probablement dans ce cas un ancien horizon de travail, et devrait être nommé en toute rigueur Ap_2 plutôt que E ou Bt dans les profils sous culture. La dénomination E ou Bt que nous avons utilisée comme les auteurs qui nous précèdent (Mitsuchi *et al.*, 1986; Imsamut et Boonsompoppan, 1999; Bruand *et al.*, 2004) n'est cependant pas illogique dans la mesure où cet horizon présente en général des phénomènes d'éluviation et illuviation (Annexe 2).

Effondrement de la structure

L'effondrement de la structure apparaît comme la seconde étape de la densification. Cet effondrement, qu'il soit provoqué sous une pression mécanique faible ou sous le propre poids du sol, correspond à la disparition de la majeure partie de la macroporosité de l'arrangement d'agrégats, c'est à dire au passage d'une structure granulaire métastable (constituée d'agrégats et de sables libres) à une structure massive. La disparition de cette macroporosité se traduit par une importante augmentation de la densité apparente détectable par la mesure de densité apparente sur cylindres. Les observations de terrain comme les commentaires des agriculteurs nous ont amené à faire l'hypothèse que cet effondrement se produit dès les premières pluies (survenant après travail du sol) et sous de faibles pressions.

Une expérimentation en conditions contrôlées a été conduite afin de déterminer les propriétés d'effondrement de massifs d'agrégats simulant la structure granulaire métastable décrite précédemment. L'expérience (Annexe 4) a consisté à humecter un massif d'agrégats secs confiné sous différentes pressions allant de quelques kPa à 1500 kPa. Le mode opératoire, décrit en détail dans l'annexe 4, était proche des expériences réalisées sur des matériaux plus fins par Assallay *et al.* (1996; 1997). Nous avons dans le cas présent apporté une attention particulière à déterminer la teneur en eau critique de l'effondrement.

Nous avons ainsi pu démontrer que les sols sableux de la région sont extrêmement sensibles à l'effondrement dès lors qu'ils contiennent une faible quantité d'argile. Des massifs de sable sans argile ne s'effondrent pas (Annexe 4, Figure 4). L'argile, principalement de la kaolinite dans ces sols, est un facteur clef du processus, dans la mesure où elle est non seulement nécessaire à la constitution de l'ensemble métastable, mais de plus sa teneur dans les agrégats détermine l'amplitude de l'effondrement ainsi que l'humidité critique auquel il se produit. Le massif s'effondre sous de faibles pressions (probablement < 25 kPa), la densité apparente finale étant corrélée à la pression appliquée. L'effondrement se produit à de très faibles humidités (5-10 %) et l'intensité de l'effondrement est donnée par les courbes de tassement en sec et humide (Annexe 4, Figure 3).

En conclusion, les sols du Nord-est, et plus généralement les sols sableux contenant de faibles teneurs en argile sont susceptibles de s'effondrer sous de faibles pressions et à de faibles humidités dès lors qu'ils sont travaillés.

Réarrangement des constituants

Le processus d'effondrement explique bien la reformation rapide de l'horizon compact après les premières pluies mais il n'explique pas complètement les fortes densités observées au champ (Annexe 4, Figure 7). L'effondrement de la structure conduit à une structure massive par disparition simultanée des agrégats et des macropores. Cependant, ce processus explique mal le remplissage très compact observé dans les sols, où limons et argiles viennent combler les espaces entre les grains de sables formant une structure quasi-continue (Bruand *et al.*, 2004).

Le processus conduisant à un assemblage si serré ne peut correspondre à un simple effondrement, dans la mesure où le déplacement des grains qui viennent combler le matériau nécessite une énergie d'autant plus importante que le matériau est dense. Par ailleurs, si l'effondrement décrit précédemment n'a pas conduit à ce type d'arrangement, nous ne sommes plus maintenant en présence d'un matériau granulaire et instable mais d'un matériau continu et massif, ce qui exclut l'hypothèse d'effondrements successifs. Le phénomène conduisant à un tel réarrangement est par contre possible lors d'une succession de pression-relaxation, dans la mesure où la pression dégage suffisamment d'énergie pour dépasser les forces de frottement entre les grains et la relaxation permet aux forces de frottement de se réduire et aux grains de se réarranger. Cette hypothèse implique que le matériau est peu élastique, sinon la succession de pression-relaxation ne permettrait pas de modifier l'organisation du matériau.

Nous avons réalisé une seconde expérience en utilisant le dispositif et les échantillons mentionnés dans l'étude de l'effondrement (expérience présentée également en Annexe 4). L'expérience a consisté à faire subir aux échantillons une succession de pressions et de relaxations dans un milieu saturé d'eau mais drainant. La pression appliquée était toujours la même pour une succession de pressions et de relaxations donnée, et l'expérience a été réalisée avec différentes pressions.

Cette expérience nous a permis de monter que le réarrangement est susceptible d'augmenter significativement la densité d'un échantillon préalablement effondré (Annexe 4). A ce niveau de la discussion il est important de rappeler quelques considérations relatives aux propriétés mécaniques des sols. Le principe de la pré-consolidation implique qu'un sol donné (ou un massif d'agrégats) consolidé à une pression P1 et ayant une densité apparente D1, doit être soumis à une pression P2 > P1 pour que sa densité augmente. La variation de densité apparente traduit une consolidation du matériau. Dans notre cas, l'application d'une pression égale à la pression de pré-consolidation induit un nouveau tassement dès lors qu'une phase de relaxation a eu lieu. En conséquence le principe de consolidation n'est pas applicable en l'état. Une succession de pressions et de relaxations (accroissement et relâchement des contraintes), avec toujours la même intensité maximale de pression, entraîne ainsi un tassement progressive jusqu'à atteindre une asymptote de densité apparente (Annexe 4, Figure 6).

Résistance à la pénétration

La densification des sols provoque souvent une augmentation de leur résistance à la pénétration (Guérif, 1994). Les fortes résistances à la pénétration conduisent quant à elles à des problèmes d'enracinement (Hartmann *et al.*, 1999). Si la mesure de la résistance à la pénétration se fait de façon relativement aisée, que ce soit à l'aide un pénétromètre de surface ou d'un pénétromètre de poche comme nous l'avons fait dans les Annexes 2, 3 et 7, la connaissance de son origine est plus compliquée. En effet, de nombreux phénomènes se surimposent et interagissent pour expliquer la résistance à la pénétration. Certains sont induits par les conditions de la mesure comme l'humidité, d'autres sont directement liés à la densité, d'autres encore sont l'expression de propriétés des constituants. La Figure 5 tente de synthétiser les interactions entre ces composantes et de clarifier la notion de dégradation. Les modifications induites par l'usage des terres sont des dégradations alors que l'expression de propriétés du matériau sont des conséquences de la dégradation.

Hardsetting

Le hardsetting traduit une importante augmentation de la résistance à la pénétration en condition sèche. Le processus du hardsetting passe dans un premier temps par l'effondrement de la structure (Mullins *et al.*, 1990). Cet effondrement, qui peut être d'origine anthropique ou pédogénétique, conduit les grains les plus grossiers à être liés par de l'argile qui rend le système extrêmement solide en condition sèche. Le hardsetting concerne les sols dont les argiles sont non gonflantes et qui ne sont pas capables de se restructurer lors des cycles humectation-dessiccation (Mullins *et al.*, 1990). Il apparaît clairement sur les profils décrits dans les 2 séquences, que la plupart des sols présentent de fortes résistances à la pénétration en profondeur en condition sèche. L'horizon Bt est alors le plus sujet à ce type de phénomène (Annexe 2). L'effondrement et le réarrangement décrit précédemment favorisent également le hardsetting dans la mesure où la structure devient continue. Cependant, les fortes résistances à la pénétration dues au hardsetting ne s'exprimeront que lorsque le sol est sec.

La cimentation par des oxydes de fer

Le sol peut être complètement cimenté par un agent liant comme le fer, c'est le cas des Plinthites ou des sols cuirassés (Eswaran *et al.*, 1990). La couleur rouge des sols ferralitiques, les cuirasses qui affleurent sur certaines hauteurs, les nodules ferro-manganésien observés dans les profils où encore les nombreuses taches d'oxydoréduction qui colorent les profils des bas fonds, traduisent l'importante dynamique du fer dans les sols de la région (Annexe 2). Cependant, à l'exception des cuirasses qui peuvent se trouver à faible profondeur dans les sols squelettiques, on ne retrouve pas de cimentation dans les profils de sols observés et la cimentation par le fer n'est pas à l'origine des fortes résistances à la pénétration mesurées.

La cimentation par de la silice

La cimentation par de la silice est un phénomène susceptible d'intervenir dans les zones soumises à de fortes contraintes physico-chimiques et climatique. De tels phénomènes conduisent à la formation d'un matériau extrêmement résistant en sec comme en humide. Les conditions physico-chimiques et climatiques de mobilisation de la silice sont envisageables dans nos sols (Annexe 8), mais les observations macroscopiques (Annexe 2) et micro-morphologiques (Annexe 3), n'ont révélé que peu d'occurrence de cimentation des grains par la silice. Par contre, l'étude exoscopique que nous avons conduite sur un sol représentatif de la région a mis en évidence des phénomènes de dissolution et de précipitation (Annexe 5). Cette étude basée sur la comparaison, d'une part du sol au matériau parental et, d'autre part des différents horizons de sol entre eux, a révélé les traces d'une importante dynamique de la silice à l'échelle pédogénétique mais aussi à l'échelle de la mise en culture. Nous avons montré en effet que les quartz des sols présentent de nombreuses traces de dissolution et de précipitation de silice alors que le matériau parental en est indemne. Par ailleurs, les tendances respectives à la dissolution et à la précipitation ont été évaluées en fonction de la profondeur dans le profil de sol. Il ressort de ces données semi-quantitatives (Annexe 5, Figure 4), que les horizons de surface (Ap) et sous-jacents à l'horizon compact (E ou Bt) présentent majoritairement des marques de dissolution. Inversement, l'horizon compact (E) présente des figures de précipitation fraîches qui traduisent une accumulation récente de la silice dans cet horizon. Globules siliceux et fleurs de silice traduisent ainsi une dynamique actuelle de la silice qui se surimpose dans les sols cultivés aux phénomènes similaires d'origine pédogénétique.

La taille, forme et microtextures des grains

Qu'elles soient héritées du matériau parental, induites par la pédogenèse ou encore par la mise en culture, les microtextures des grains de quartz s'ajoutent aux formes et distribution en tailles qui font de ces sols des matériaux dont les frictions entre grains sont très fortes. En effet, l'angularité des grains, la présence de petits grains de quartz qui viennent remplir les interstices, et les aspérités à la surface des grains, sont autant de facteurs qui augmentent considérablement l'énergie nécessaire pour déplacer un grain par rapport à un autre dès lors que le sol est dense. A l'exception des précipitations de silice récentes, qui ne constituent pour le moment qu'une infime proportion des microtextures, et du possible fractionnement des grains, ces propriétés ne peuvent être considérées en tant que telles comme des dégradations du sol dans la mesure où elles existent déjà dans les sols non cultivés. Elles constituent cependant un ensemble de caractères propres aux sols de la région qui rendent leur utilisation problématique dès lors qu'ils subissent une dégradation physique telle que la densification.

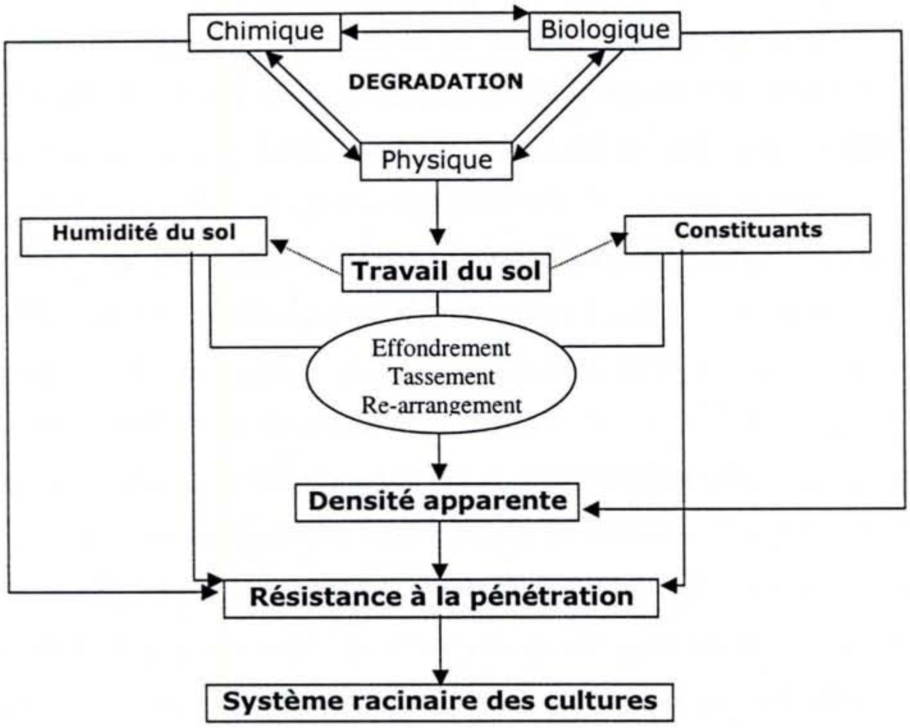

Figure 6 : Interactions des mécanismes et conséquences de la dégradation physique

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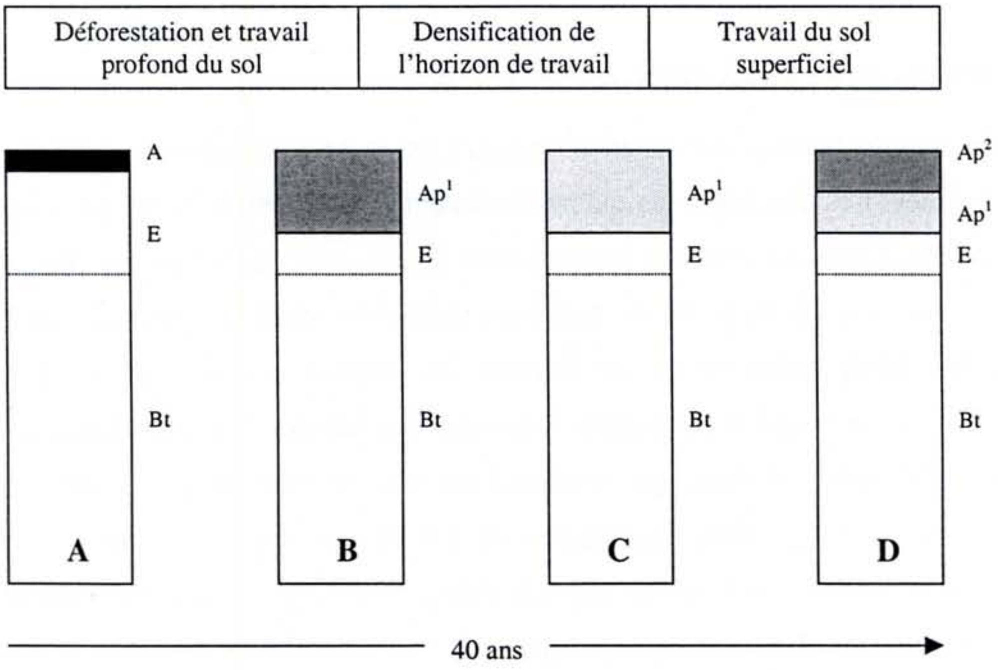

Figure 7 : Evolution du profil de sol aux cours des travaux agricoles avec (a) profil sous forêt ; (b) travail profond ; (c) effondrement de la structure de l'horizon travaillé ; et (c) travail superficiel.

Prévention et réhabilitation

Sensibilité des sols cultivés et persistance de l'horizon compact

Au vu des propriétés et mécanismes étudiés précédemment, les sols sableux de la région sont très sensibles à la dégradation physique. Ils sont sujets à une densification intense et quasi-inévitable dès lors qu'ils sont mis en culture. Les conséquences de cette densification sont extrêmes en terme de résistance à la pénétration du fait des propriétés de leurs constituants (i.e. friction, assemblage serré, hardsetting). Par ailleurs, les faibles pressions et humidités nécessaires à la re-densification de l'horizon travaillé rendent la marge de manœuvre très réduite en terme de travail du sol. La prévention de la densification ne peut alors passer que par un travail limité et/ou une amélioration de la stabilité de la structure par des apports de matières organiques. On notera que le sous-solage ou travail profond du sol ne sont en aucun cas des alternatives à la prévention de la densification, ils risquent au contraire d'aggraver le problème. L'horizon compact, dès lors qu'il est formé sur l'ensemble de la couche travaillée, constitue une structure anthropique nouvelle avec laquelle l'agriculture va devoir cohabiter. Cette structure massive, dense et résistante est extrêmement défavorable à la croissance racinaire, mais elle constitue un environnement dont il est souhaitable de maintenir la stabilité. Les options de réhabilitation s'organisent donc dans une optique visant à aider l'enracinement au-dessous de cette barrière physique tout en conservant sa stabilité structurale.

Pour faire passer les racines : moins de résistance ou plus de macropores

L'impact de la structure du sol sur le développement et la croissance des racines est un sujet qui a reçu beaucoup d'attention cette dernière décennie (Passioura, 1991; Stirzaker *et al.*, 1996; Angers et Caron, 1998). Il a été montré que la prolifération des racines est étroitement corrélée à la présence de macropores (Hatano *et al.*, 1988; Hatano et Sakuma, 1990; Stewart *et al.*, 1999). Plusieurs études, utilisant un horizon impénétrable contenant de nombreux macropores cylindriques (Dexter, 1986), la perforation artificielle d'horizon compact (Nambiar et Sands, 1992) ou encore des macropores artificiels simulant des biopores orientés verticalement (Nakamoto, 1997), ont confirmé l'importance de la macroporosité dans l'amélioration de l'enracinement d'une culture.

Compte tenu des caractéristiques des sols, réduire la compaction des sols sableux n'est pas chose simple. Les techniques classiques de sous-solage, qui consistent à briser la couche compacte, se sont avérées inefficaces. Loin de diminuer la compaction, les observations de terrain et les résultats agronomiques montrent que le sous-solage s'est traduit après quelques mois par une compaction au moins équivalente à l'état initial, ce qui n'a finalement pas permis le développement correct de la plante et en conséquence d'augmenter les rendements. Les sols sableux deviennent très instables lorsqu'ils sont travaillés en profondeur et s'effondrent sous de faibles pressions dès les premières pluies. D'un autre côté, étant donné leur caractère non gonflant, ces sols sableux ne sont pas capables de générer d'eux-mêmes une macroporosité. Leur faible teneur en argile et la faible capacité de la faune à modifier la structure (lombrics, termites) rend inefficace la jachère. Ces caractéristiques ont conduit à orienter les recherches vers des techniques permettant de bénéficier de la rigidité propre au matériau et de créer des zones poreuses en nombre limité mais suffisamment stables dans le temps pour qu'elles permettent le passage des racines.

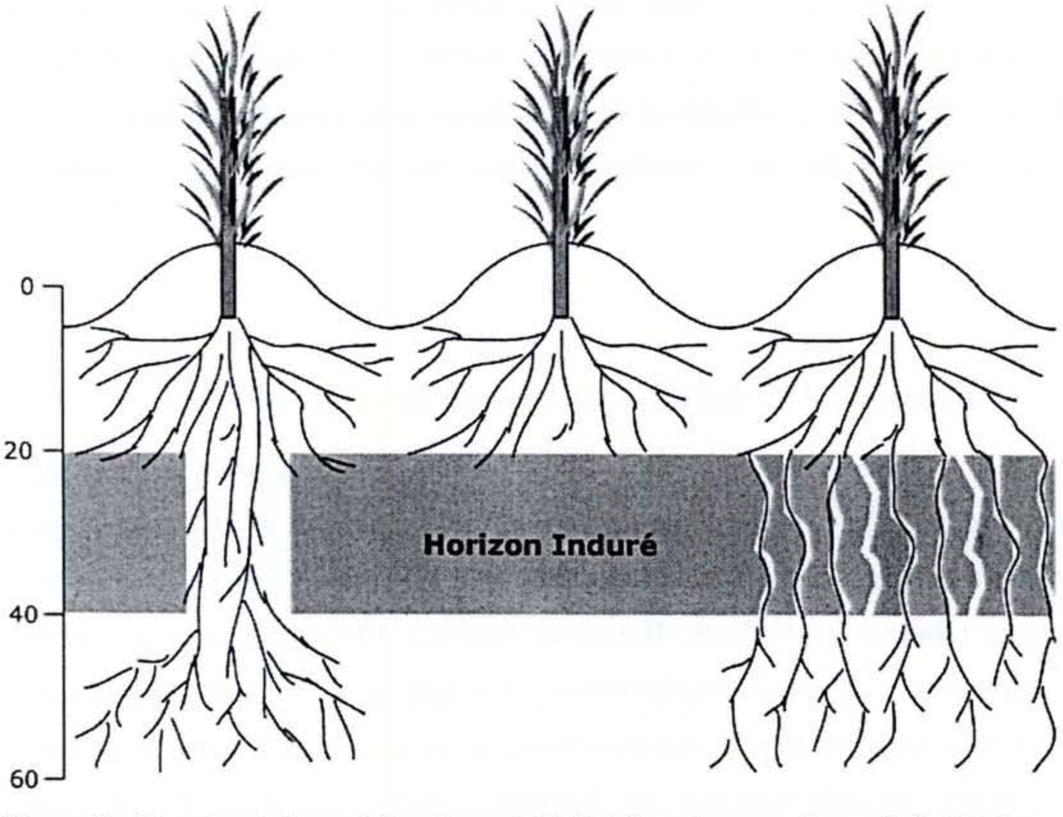

Figure 8 : Représentation schématique de l'effet du rainurage (à gauche) et de la bio-perforation (à droite) sur l'enracinement d'une culture dans un sol présentant un horizon fortement induré.

Dans ce but, deux approches ont été étudiées (Figure 8). La première consiste à préparer un matériau hétérogène avec un travail du sol localisé (le rainurage) ; la seconde consiste à utiliser une plante capable de perforer l'horizon compact avant de mettre en place la culture (bio-perforation). L'hypothèse dans les deux cas est que des zones de passage sont créées pour les racines à travers l'horizon compact, mais l'horizon compact, qui constitue une armature stable, n'est pas complètement détruit. De fait, l'horizon compact doit aider à maintenir la stabilité du système et éviter l'effondrement du sol.

Réhabilitation mécanique (travail du sol efficace)

Le rainurage consiste à travailler le sol en profondeur mais uniquement sous les lignes de plantation (Jayawardane *et al.*, 1995). Des rainures d'environ 10 cm de large sont creusées au travers de l'horizon compact et comblées ensuite avec le sol originel ameubli. La partie restée compacte forme alors un squelette solide qui supporte le poids des couches de surface et les pressions appliquées.

Cette technique a été testée sous différentes cultures et s'est avérée très efficace. L'étude du système racinaire des plantes a montré que les racines se sont intensément développées dans les fentes et dans le sol sous-jacent à la couche compacte. Ce développement du système racinaire favorise une meilleure alimentation en eau de la plante et le prélèvement plus important des éléments minéraux en profondeur. Les rendements de différentes cultures, telles que le niébé (*Vigna unguiculata*) ou le maïs (*Zea mays*) ont ainsi pu être significativement augmentés jusqu'à un an et demi après le creusement des rainures. Réalisable avec du matériel simple, le rainurage est moins coûteux qu'un labour profond et il permet de maintenir pendant au moins deux ans les bénéfices générés par le travail du sol (Hartmann et Poss, 1999).

Le rainurage augmente la porosité et réduit la résistance

Nous avons conduit une expérimentation en station afin de mettre en évidence les modifications structurales, induites par le rainurage, pouvant expliquer la prolifération des racines dans les rainures (Annexe 6). L'organisation porale d'échantillons prélevés dans l'horizon compact a été comparée à celle d'échantillons prélevés à même profondeur dans la rainure. Une approche combinant micromorphologie, rétention d'eau et porosimètrie mercure a permis de caractériser la porosité à différentes échelles. Il ressort de cette étude que l'augmentation flagrante de porosité dans les rainures affecte deux niveaux de porosité. La première concerne la macroporosité, la seconde, la porosité fine qui correspond au mode d'assemblage limon-sable, origine de la forte résistance à la pénétration. Le premier mode traduit donc une meilleure aération, et le deuxième mode, un assemblage moins serré entre les grains.

Le rainurage permet d'augmenter significativement la porosité du sol au travers de l'horizon compact. Les bénéfices de ce travail sont plus durables que dans le cas d'un sous-solage dans la mesure où la structure stable de l'horizon compact reste entière entre les rainures, et offre par conséquent une meilleure résistance au tassement. D'autres hypothèses impliquant la physique des milieux granulaires, et particulièrement les effets d'arche, sont aussi à prendre en considération (Hartmann *et al.*, 2002).

Réhabilitation biologique (bio-perforation de l'horizon compact)

Relations sol-racines et effet des biopores

Faire pousser des plantes qui ont un système racinaire fort a le potentiel d'améliorer les sols dégradés par bio-perforation (Cresswell et Kirkegaard, 1995). Les racines mortes laissent un réseau continu de macropores verticaux que la culture suivante peut utiliser (Volkmar, 1996; Angers et Caron, 1998). Une plante à enracinement profond peut potentiellement améliorer l'enracinement de la culture suivante, et par conséquent améliorer son alimentation et ses rendements (Salako *et al.*, 2002). Il a été montré par exemple qu'un sol limoneux-sableux, sévèrement compacté, peut être amélioré par une plante de couverture par l'intermédiaire des effets combinés des mulchs organiques et de la bio-perforation (Stirzaker et White, 1995). A l'autre extrême textural, Pillai et McGarry (1999) ont montré que les racines des plantes étaient capables d'améliorer considérablement la structure d'un vertisol (effet des racines combiné aux cycles d'humectation-dessiccation).

Les espèces végétales qui perforent

Toutes les plantes ne sont pas égales face à la compaction et résistance à la pénétration des sols. Même si un horizon compact ou induré représente dans tous les cas une limite à l'enracinement, il se traduira tantôt par une diminution des impacts racinaire au passage de l'horizon et tantôt par une limite qui n'est franchie par aucune racine. *Stylosanthes hamata* a la capacité de développer un important système racinaire même dans des conditions de structure adverses. Il a par ailleurs été montré que l'introduction de cette légumineuse dans des pâtures tropicales induit une augmentation significative du nombre de macropores par le processus de bio-perforation (Bridge *et al.*, 1983). Cette espèce est par conséquent adaptée pour améliorer la qualité des systèmes agropastoraux (Miller *et al.*, 1991; Oikeh *et al.*, 1998). Cependant, la culture de cette légumineuse en rotation n'a pas montré d'amélioration structurale des sols (Ruaysoongnern et Aitken, 1980). Ceci peut être dû au fait que *Stylosanthes* nécessite plusieurs années pour développer un système racinaire conséquent (Bridge *et al.*, 1983).

Utilisation du **Stylosanthes** *comme bio-perforateur*

Une étude a été réalisée en station expérimentale afin de tester l'aptitude de la légumineuse *Stylosanthes hamata* (stylo) à améliorer la structure d'un sol sableux sévèrement compacté sous l'horizon de travail (Annexe 7). L'étude a montré que la culture continue du stylo induit la formation de nombreux macropores au travers de l'horizon compact. Ces bio-pores restent ouverts après la dégradation des racines de stylo et la culture suivante bénéficie alors de nombreux passages pour explorer le sol en dessous de la zone résistante. Par ailleurs, du fait qu'ils traversent la structure massive et stable de l'horizon compact, ces bio-pores sont durables à moyen terme. Il a pu être montré qu'en deux ans de culture continue de stylo, le nombre de macropores traversant l'horizon compact est triplé. Ces bio-pores ont significativement amélioré l'enracinement et la croissance du maïs qui a été cultivé ensuite.

Problèmes d'acidification des sols

Une étude de l'acidification des sols sous *Stylosanthes* a été menée en parallèle (Annexe 8). Des parcelles cultivées sous rotation stylo-maïs ont été comparées à des parcelles cultivées sous *Stylosanthes* continu. Le taux d'acidification sous une culture continue de la légumineuse est bien plus élevé que lorsque la culture est en rotation. Ce taux d'acidification est étroitement corrélé à l'exportation alcaline générée par les récoltes car l'alcalinité des cendres du *Stylosanthes* est très importante. Dans le cas particulier du Nord-est thaïlandais, l'acidification passe inaperçue dans une situation non chaulée, suggérant que les sols sont fortement tamponnés à un pH de 4.0 (mesure au $CaCl_2$ 0.01M).

La bio-perforation fonctionne et augmente la croissance racinaire

La bio-perforation fonctionne en cultivant de façon continue le *Stylosanthes*. L'horizon compact se retrouve alors perforé de nombreux macropores qui sont autant de passages pour les racines de la culture suivante. On observe en effet une augmentation significative de l'enracinement du maïs. Cependant, les résultats attendus en terme de rendement n'ont pas suivi l'amélioration de l'enracinement. Différents facteurs sont susceptibles d'expliquer ce phénomène. L'acidification que nous avons étudiée (Annexe 8), ne peut être traduite directement en terme de baisse de pH. En effet, tout se passe comme si le sol avait, au pH considéré un pouvoir tampon considérable qui a été attribué à la dissolution des kaolinites, laquelle est à l'origine de la libération d'aluminium et en conséquence d'une possible phytotoxicité aluminique. Egalement, de possibles messages hormonaux peuvent réguler la croissance des plantes lorsque la racine rencontre un horizon compact, et même si elle trouve le passage ensuite.

Conclusions

Le Nord-Est de la Thaïlande est un exemple marqué de dégradation physique des sols sableux. Loin d'être inertes sur le plan structural, les sols sableux constituent une ressource fragile qui nécessite un mode de gestion adapté.

Nous avons d'abord montré que la majorité des sols de la région se sont développés sur un matériau sableux d'origine éolienne. Le manteau sableux qui recouvre la région a été transporté sur de longues distances dans des conditions de forte énergie. La distribution de tailles des grains de quartz ainsi que leurs propriétés de surface sont ainsi des caractères hérités du matériau parental. Ceci confère au sol des propriétés communes, quelle que soit l'évolution pédologique. Par la suite, la couverture sableuse s'est différenciée sous l'action du climat et a donné des sols qui se distinguent principalement par leur taux d'argile.

Ces 50 dernières années, la pression démographique a conduit à une déforestation massive et à la mise en culture intensive et mécanisée de la plupart des sols. D'ores et déjà nous constatons l'apparition à faible profondeur d'un horizon dense et résistant à la pénétration est généralisée. La persistance de cette caractéristique dans des sols déjà pauvres sur le plan chimique a conduit à considérer ces sols sableux comme problématiques pour l'agriculture. Seulement quelques décennies de ce mode de gestion ont donc suffi a considérablement dégrader les sols.

En raison de leur minéralogie et de leur faible taux de matière organique, les sols de la région sont faiblement structurés. Lorsqu'ils sont travaillés mécaniquement, la structure massive explose en une structure granulaire constituée de petits aggregats et de particules élémentaires. Cet état est apparu très instable et sujet à l'effondrement. Les expériences en conditions contrôlées ont montré que l'effondrement se produit à de faibles humidités et sous de faibles pressions mécaniques. La structure redevient alors massive et continue, et conduit à un état plus défavorable qu'avant le travail du sol dans la mesure où la porosité biologique a elle aussi disparu. Une autre caractéristique rend ces sols sensibles au tassement et explique les fortes densités observées sur le terrain : Les sols sableux évoluent vers un arrangement de plus en plus serré des grains lorsqu'ils sont soumis à des cycles de pression relaxation. Dès lors que le sol est dense, les propriétés du matériau associées à la géométrie des grains s'expriment par une forte résistance à la pénétration. La distribution de tailles des sables mais l'angularité et les propriétés de surface héritées du matériau parental en sont la cause principale. La précipitation préférentielle de la silice dans l'horizon compact est un facteur qui contribue à aggraver ce phénomène.

Nos travaux de terrain ont montré que dans de tels sols sensibles à l'effondrement, le travail du sol conventionnel peut avoir des effets adverses car la destruction de la structure massive rend le sol très instable. Loin d'améliorer la porosité du matériau, il conduit souvent à des densités au moins équivalente à l'état initial. Cependant la gestion de ces sols peut passer par un travail localisé comme le rainurage ou par la bio-perforation. L'objectif étant dans les deux cas de créer localement des zones de passage pour les racines tout en conservant le reste du sol dans sa structure la plus stable.

Cette étude a montré que les sols du Nord-Est Thaïlandais possèdent des caractéristiques communes. Dans le passé ces sols ont été classés en fonction de critères adaptés à leur mise en valeur et pour l'aménagement du paysage agricole. Partant d'une approche plus générale basée sur l'origine des matériaux et de leurs conditions de formation, il devient possible de répondre aux questions que posent les dégradations généralisées consécutives à la mise en culture. Au plan fondamental, les sols sableux sont des matériaux modèles pour étudier les relations physiques entre les constituants, cependant l'argile qu'ils contiennent les distingue radicalement des milieux granulaires purs. Les sols sableux ont des comportements physiques tout à fait originaux et la prise en compte de leurs propriétés spécifiques notamment au plan des propriétés mécaniques est nécessaire pour développer des outils de gestion durables des agro-systèmes.

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Annexes

Annexe 1

The aeolian origin of Quaternary deposits and soils in Northeast Thailand

André Prone, Grégory Lesturgez, Roland Poss & Montree Boonsener

Origine éolienne des dépôts Quaternaires et sols du Nord-Est Thaïlandais

Les dépôts Quaternaires et les sols du Nord-Est Thaïlandais sont classiquement attribués à des terrasses anciennes du Mékong. L'objectif du travail a été de déterminer cette origine à partir de l'étude des grains de quartz d'un ensemble de formations et de sols représentatifs. Des échantillons de 11 formations sédimentaires et d'un sol de la région de Khon Kaen ont été étudiés en utilisant l'approche micromorphogénique, une combinaison d'analyse granulométrique, morphoscopique, exoscopique et endoscopique. La similarité de la répartition des classes granulométriques (mode 125 µm), la présence de grains « rond mates » et « non-usés évolués » dominants et les nombreuses traces d'impacts (cupules, croissants et V de choc) prouvent l'origine éolienne de haute énergie des dépôts Quaternaires étudiés. Des stries de frottement et traces de broyage mettent en évidence un épisode périglaciaire antérieur, et la présence de quartz rhyolitiques automorphes, inconnus dans les roches encaissantes de la région, indique une source lointaine de ces formations. Cet ensemble de résultats montre que tous les matériaux Quaternaires assimilés à la couverture sableuse et les sols étudiés sont dérivés de dépôts éoliens probablement transportés depuis la Chine du Sud.

The aeolian origin of Quaternary deposits and soils in Northeast Thailand

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Abstract

Usually, the soils and Quaternary deposits of Northeast Thailand are attributed to ancient terraces of the Mekong River. The objective of the study was to challenge this interpretation by studying quartz sand grains from a series of representative soils and deposits. Samples from 11 sedimentary deposits and one soil of the Khon Kaen region were studied. The micromorphogenic approach which combines particle size determination with morphoscopy, exoscopy, and endoscopy was used. The samples had the same sand particle size distribution (mode 125 µm), the shape of the grains was mainly "round-frosted" or "unworn evolved", and the surface of all the grains showed numerous impact marks (cupules, crescent-shaped and V-shaped features). These features are evidence of high energy aeolian transportation. Friction streaks and crushing traces inferred a previous periglacial period. Automorphic rhyolitic quartz crystals, unknown in the bedrock of the region, indicated a remote origin. These results prove that all the Quaternary deposits related to the sandy cover and the soil studied were derived from the same aeolian deposits, probably having been transported by wind from southern China.

Introduction

The topography of Northeast Thailand has an undulating plateau with gentle slopes and wide valleys developed over a secondary area sedimentary basin (Maha Sarakham), approximately 250 metres thick; it is comprised of sandstones and detrital conglomerates. Most of the region is covered with a thick (exceeding five metres) and uniform sandy layer often called the "cover layer". This layer has been described in Vietnam, Cambodia, Myanmar, in the uplands of Malaysia, and even in India (Hoang Ngoc, 1989; 1994). While most authors agree it is the parent material of the soils, they differ in their interpretation of its origin.

The most quoted work is by Moormann *et al.* (1964). The authors described the distribution of the soils of Northeast Thailand using a geomorphologic model. They suggested that most of the soils derived from Quaternary alluvial deposits of the Mekong River and its tributaries. They identified three levels of terrace, which they termed "high", "middle", and "low". They described the high terrace as consisting of pebbles, sand, silt, and clay, while the middle and low terraces comprised pebbles, sand, silt, clay, and laterite. On the geological map of Chaiyaphum district (Vimuktanandana, 1985), the sandstones and conglomerates appear to be divided up into strips by the high terrace. Near the valley, the high terrace resembles a wide band aligned with a narrow strip of low terrace. Further south, the sandstones and conglomerates are festooned with dendritic terraces, whose fan shape is related to the loose meandering of the local rivers. These meanders, together with the many river branches, are partly related to the cessation of the regressive erosion by the quartzite sandstone ridge that fringes the sedimentary basin. However, the intensity of the phenomenon is such that other processes can be anticipated.

Several authors have challenged the alluvial origin of the so-called terraces (Michael, 1982; Boonsener, 1983; Löffler *et al.*, 1984; Pramojanee *et al.*, 1985; Dheeradilik and Chaimanee, 1986; Tamura, 1992). Michael (1982) advocated a colluvial origin. As early as 1983, Boonsener suggested an aeolian origin, because the particle size distribution of the sand grains was typical of aeolian deposits. Hoang Ngoc (1989; 1994), Sibrava (1993), and Sibrava and Shimanovich (1994) supported the aeolian origin in Vietnam and Thailand. However Pramojanee *et al.* (1985) proved that, in at least one case, the particle size distribution of the sand grains was identical to the distribution in the sandstones and conglomerates. Löffler and Kubiniok (1996) considered the superficial sandy layer to be the result of *in situ* bioturbation, the constant addition of fine particles by termites being the cause of the observed particle size distribution. However, Sanderson *et al.* (2001) proved, using luminescence, that the quartz grains in the surface horizons were not of the same age as the quartz grains in the deeper horizons. They advocated the aeolian sand interpretation, but could not prove it.

The objective of this study was to determine the origin of the main Quaternary deposits and a typical soil of the Khon Kaen region using micromorphogeny (Prone, 2003). This approach, which combines the determination of the particle size distribution, and the morphoscopic, exoscopic, and endoscopic description of the sand grains, allows an exact determination of how the grains were transported.

Material and methods

The samples

Samples of Quaternary deposits were taken from so-called alluvial deposits and Quaternary terraces on a 35-km transect near Khon Kaen from 35 km south to 10 km north of the city (Fig. 1). We retained the terminology mentioned in the geological maps of Vimuktanandana (1985):

1. Grey and yellow sandstones of the Phu Phan formation
2. "Dune sands" in the Maha Sarakham formation
3. "Fine sands" in the Maha Sarakham formation
4. Silty-clay material in Quaternary alluvial deposits
5. Conglomerates in Quaternary alluvial deposits
6. Red and white sandstones and conglomerates in Quaternary terraces
7. Silty-clay material in Quaternary terraces
8. Red sandstone and silty-clay material in Quaternary alluvial deposits

Another series of samples was taken in the low terrace of the Quaternary alluvial deposits of *Amphoe*[6] Nong Song Hong (40 km south of Khon Kaen):

9. Silty clay material in the upper part of the low terrace
10. Soil horizons (10 cm, 20 cm, and 40 cm) in the lower part of the low terrace of *Amphoe* Nong Song Hong (35 km south of Khon Kaen)
11. Silty clay material in the lower part of the low terrace.

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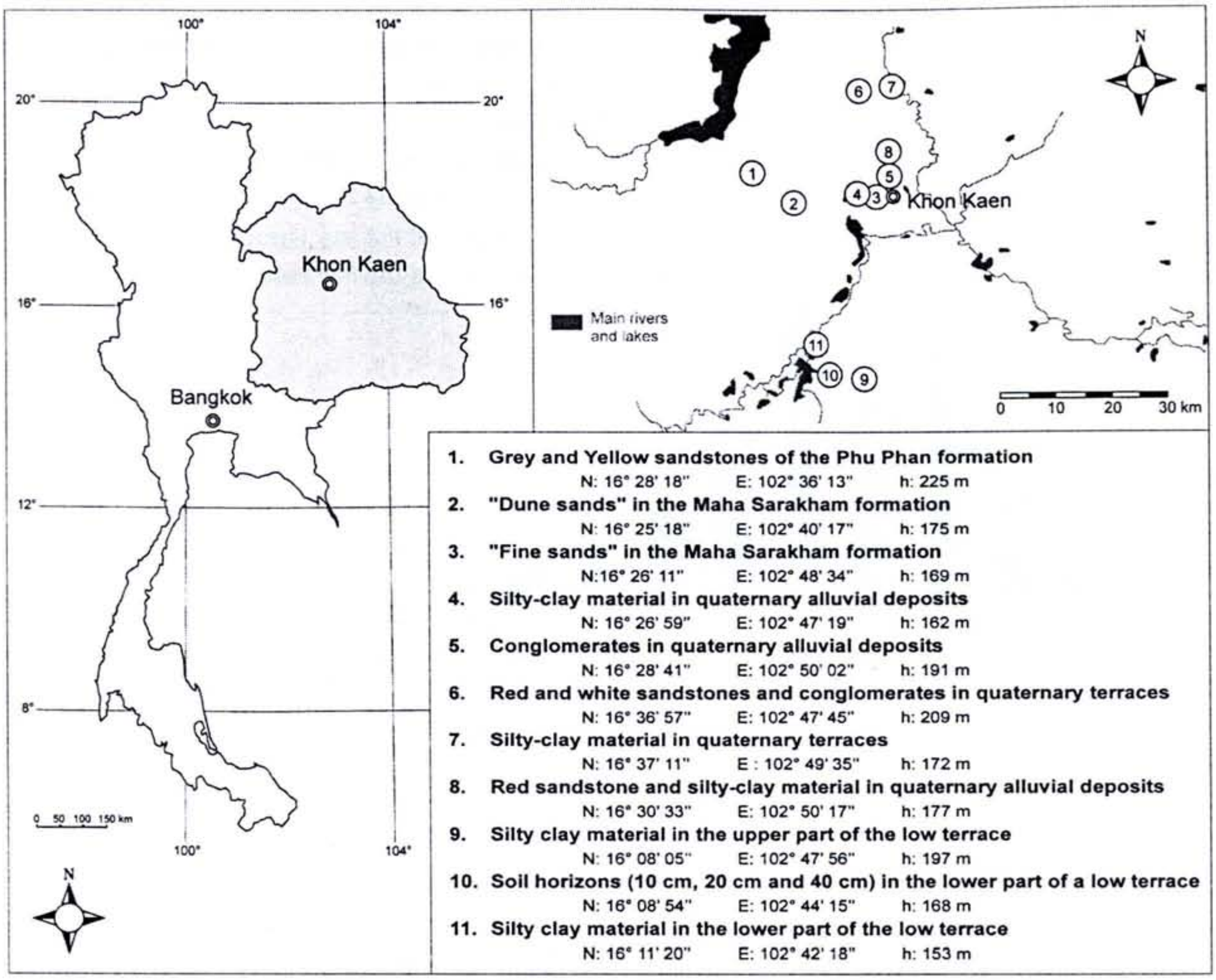
[6] An *Amphoe* is an official administrative district in Thailand.



1.	Grey and Yellow sandstones of the Phu Phan formation	N: 16° 28' 18"	E: 102° 36' 13"	h: 225 m
2.	"Dune sands" in the Maha Sarakham formation	N: 16° 25' 18"	E: 102° 40' 17"	h: 175 m
3.	"Fine sands" in the Maha Sarakham formation	N:16° 26' 11"	E: 102° 48' 34"	h: 169 m
4.	Silty-clay material in quaternary alluvial deposits	N: 16° 26' 59"	E: 102° 47' 19"	h: 162 m
5.	Conglomerates in quaternary alluvial deposits	N: 16° 28' 41"	E: 102° 50' 02"	h: 191 m
6.	Red and white sandstones and conglomerates in quaternary terraces	N: 16° 36' 57"	E: 102° 47' 45"	h: 209 m
7.	Silty-clay material in quaternary terraces	N: 16° 37' 11"	E : 102° 49' 35"	h: 172 m
8.	Red sandstone and silty-clay material in quaternary alluvial deposits	N: 16° 30' 33"	E: 102° 50' 17"	h: 177 m
9.	Silty clay material in the upper part of the low terrace	N: 16° 08' 05"	E: 102° 47' 56"	h: 197 m
10.	Soil horizons (10 cm, 20 cm and 40 cm) in the lower part of a low terrace	N: 16° 08' 54"	E: 102° 44' 15"	h: 168 m
11.	Silty clay material in the lower part of the low terrace	N: 16° 11' 20"	E: 102° 42' 18"	h: 153 m

Figure 1: Location of the sampling sites, GPS coordinates and altitude.

Sample preparation

Using the theoretical relationship of Gy (1988) it was estimated that 10 kg of samples were necessary to reach a relative accuracy of 15%. At each site 10 1-kg samples were taken from a pit from a layer 5-cm thick. The 10 samples were mixed thoroughly and homogenized to form a 10-kg primary lot. This lot was split up using a mass separator to give a 1-kg representative sample.

Particle size distribution of the sand

A representative 150-g sub-sample was extracted using a mass separator. The sand fraction (>50 µm) was extracted by sedimentation after hydrogen peroxide pre-treatment and dispersion with sodium hexametaphosphate. The particle size distribution of the sand fraction was determined on the entire sub-sample using a vibrating column of 16 sieves.

Morphoscopy

The morphoscopic analysis describes the sand grains using a low-power stereo microscope. The grains were split into four size fractions to avoid overlapping:

- 2–0.5 mm fraction (coarse sand)
- 0.5–0.2 mm fraction (medium-sized sand)
- 0.2–0.1 mm fraction (fine sand)
- 0.1–0.05 mm fraction (very fine sand).

Five samples of 400 grains were collected for each fraction. The grains were spread on a 24x36 mm piece of black graph paper and the following parameters were determined:

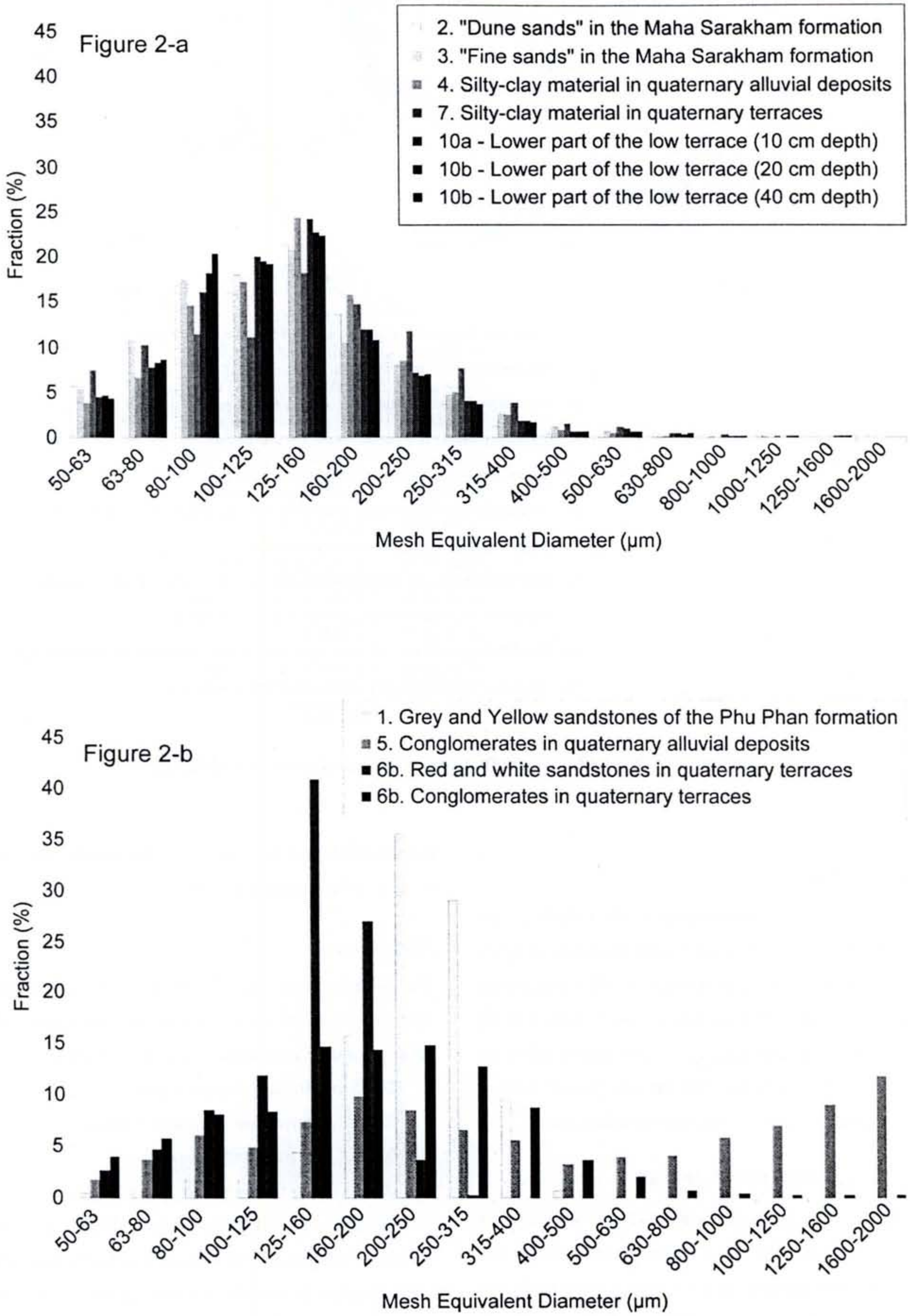


Figure 2: Particle size distribution of the sand fraction.

Shape: massive, elongated, sub-elongated, hexagonal;
Color: transparent, translucent, opaque, rusty;
Cracks: isolated, multiple, open, crossing inclusions;
Environmental parameters (Prone, 2003): Round Frosted (RF), Blunt Shining (BS), Unworn Evolved (UE), and Unworn (U).

The results from the five samples were compared using the Student Test. As they were never different ($P<0.05$) their mean was considered as representative of the particle size fraction. Thus the mean values are the result of 2,000 determinations.

Exoscopy

The exoscopic analysis was conducted on grains with the same environmental parameter using a scanning electron microscope. Due to time constraints, only 100 grains were observed for each size fraction.

In the first step, four batches of 25 grains were taken at random and examined under a low-power stereo microscope for each environmental parameter; the shape of the grains was described for each batch. As the morphoscopic parameters (shape, color, cracks) did not differ between batches ($P<0.05$), each batch was considered as representative of its environmental parameter. The exoscopic analysis was carried out on one batch of 25 grains for each environmental parameter. When, for any given environmental parameter, the number of grains was lower than 25, all the grains (n) were studied and n/3 extra grains were taken from each of the three other environmental parameter batches to reach 25 grains.

In the second step, the 25 grains were lined up on a brass block covered with double-sided tape. They were then covered with gold, introduced in the electron microscope, and described according to Le Ribault (1977). A total of 1,300 pictures were taken.

Endoscopy

The quartz grains were included in a synthetic resin and observed between slide and cover glass using a polarizing microscope. In order to describe the same grains by exoscopy and endoscopy, the grains observed with the scanning electron microscope were demetallized using *aqua regia*[7]. The inclusions were described according to Clochiatti (1975) and Prone (1980).

Results

Sand particle size distribution

The particle size distribution of the sand was homogeneous for sites 2, 3, 4, and 7, and for the soil (site 10), at a mode of 125 µm (Fig. 2a). The grey and red sandstone and the conglomerates had a different sand particle size distribution (Fig. 2b).

Morphoscopy

The morphoscopic parameters of all samples were homogeneous, except for the grey and yellow sandstones of the Phu Phan formation, where the U grains were most numerous and the RF were absent (Fig. 3). Whatever the size of the grains, the environmental parameter was mainly UE and the shape was either sub-elongated or massive. The proportion of RF grains was 30% higher in the coarse sand than in any other size fraction. The color was mainly opaque white or rust. These colors suggest a flaking of the sand grains for all the fractions. The flaking was more pronounced for the coarse sand, except for the red sandstone (site 10), and entirely rust-colored. Moreover, the edges and the tops of the grains were often blunt, carried aeolian marks, and, in some cases, showed chemical polishing. The same morphoscopic features were observed on the soil samples (site 10), except at 10 cm and at a 40-cm depth, where the surfaces of the grains were stripped of their flakes and the transparency was greater.

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[7] A mixture of nitric and hydrochloric acids that dissolves gold or platinum.

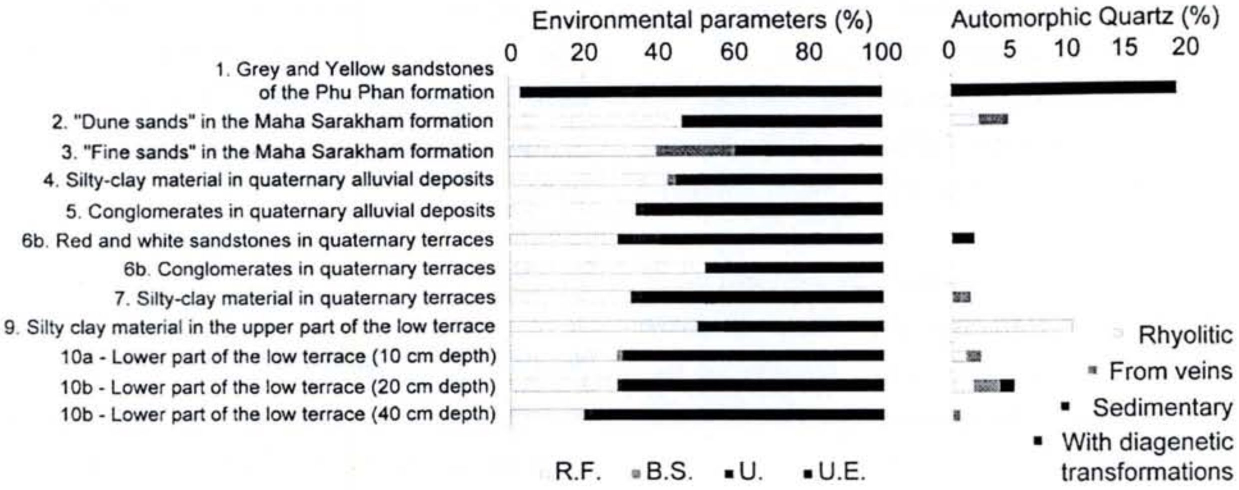

Figure 3: Morphoscopy of the quartz grains: environmental parameters and automorphic crystals.

Exoscopy

The main features observed at the surface of the sand grains are shown in Plate 1. Aeolian features were observed on the quartz grains of all the formations and of the soil, except in the grey and yellow sandstones of the Phu Phan formation. These particular features were observed on more than 60% of the quartz grains (almost 90% in the coarse sand). They included cupules, crescents of shock, and V of shock[8] (Plate 1, Picture 6) together with fish-scaling. Some samples showed many very round grains similar to actual desert RF (Plate 1, Picture 4). Sub-parallel isolated friction traces, fitted together with other chatter marks[9] (Plate 1, Picture 7) proved the high energy of the aeolian transportation. They were sometimes found together with chatter marks, typical of glacial sands (Plate 1, Pictures 8 and 9). Fracture planes of variable size, which developed preferentially where inclusions were present, were sometimes observed (Plate 1, Picture 10). Many grains had micro-cracks.

The rubefied alluvial deposits called fine yellow, red, and white sandstones on the top of the so-called low terrace were often covered with thick silicon flakes and a clayey crust, mainly made of kaolinite. They often concealed the underlying crescents of shock, V of shock, and friction features (Plate 1, Picture 5). The dissolution of the flakes at 10- and 40-cm depths in the soil (site 10), and in the surface horizon at site 9 by soil evolution, disguised the aeolian marks.

The grey and yellow sandstones of the Phu Phan formation showed traces of a fluvial origin (Plate 1, Picture 2), sometimes hidden by a thick diagenetic crystallized crust (Plate 1, Picture 1) or by large neogenetic siliceous deposits (Plate 1, Picture 3).

Endoscopy

Rhyolitic automorphic quartz crystals were observed in each size fraction of all the deposit samples and in the soil (Plate 1, Pictures 12 and 14), except in the grey and yellow sandstones of the Phu Phan formation. These automorphic crystals had vitreous diphase inclusions (Plate 1, Pictures 14 and 15). In some cases, the fluid inclusions were filled with iron oxides or clay material. These features are typical of a volcanic origin at high temperature. On the other hand, in the grey and yellow sandstones of the Phu Phan formation, the inclusions were typical of granites and micro-granites (Plate 1, Picture 13).

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[8] V shaped features induced by shocks and affecting the surface of the quartz.

[9] One of a series of short curved cracks on a glaciated rock surface transverse to the glacial striae.

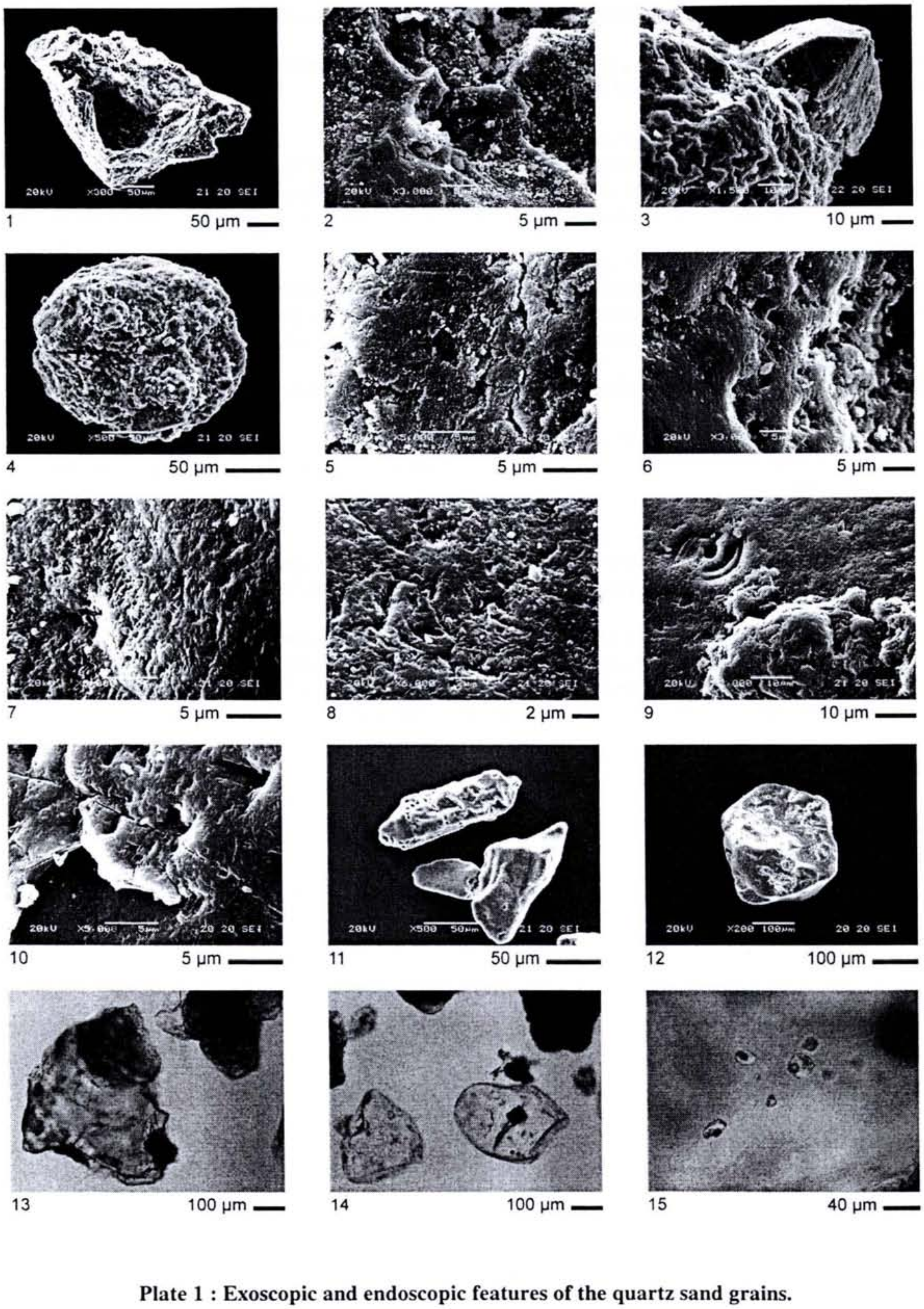

Plate 1 : Exoscopic and endoscopic features of the quartz sand grains.

Quartz grains in the grey and yellow sandstones of the Phu Phan formation

1. Unworn quartz grain with genomorphic breaks invaded by a diagenetic crystallized film and many siliceous deposits.
2. Broad slightly polished fluviatile cupules of shock filled up with siliceous deposits.
3. Large neogenetic diagenetic crystal on the summit of a quartz grain.

Aeolian quartz surveyed at the Quaternary alluvia and terraces

4. "Dirty" RF quartz grain covered with a thick crystallized film (typical feature of deserts).
5. Convex flakes of crystallizing amorphous silica showing dry exfoliation.
6. Slightly polished crescents of shock and V of shock (size > 10 µm), with siliceous deposits and globules.

Aeolian quartz surveyed at the upper part of the low terrace (site 9)

7. Encased high energy friction features, isolated friction streak, and polished crescents of shock and V of shock. The siliceous deposits and flakes have probably been lixiviated down the profile (10-cm depth).
8. Slightly polished high energy crescents of shock and V of shock, and "fish-bone" friction feature typical of periglacial aeolian quartz grains.
9. Crushing feature from glacial origin on the face of a grain, and polished siliceous neogenetic crystals.

Aeolian quartz surveyed at the lower part of the low terrace (site 10)

10. Crack generated by the comminutive fracturing of a solid inclusion. The high energy V of shock shows the aeolian transportation.

Automorphic and xenomorphic quartz grains (sites 9 and 10)

11. Automorphic and slightly worn-out xenomorphic sedimentary quartz grains showing a polishing gradient.
12. Broken automorphic rhyolitic quartz crystal with wide-open vitreous inclusion.

Quartz grains from granitic and rhyolitic origin representative of the Quaternary deposits

13. Xenomorphic quartz grain from granitic origin with weathered mica crystal and unidentified microlite.
14. Cracked automorphic rhyolitic quartz crystal. Clay minerals colonized the inclusions using the cracks.
15. Detail of vitreous inclusions of ignimbrite type with withdrawal vacuum and ferromagnesian minerals.

In the Quaternary alluvial deposits of the so-called low terrace in *Amphoe* Nong Song Hong (sites 9, 10, and 11), many inclusions had opened, due to the micro-cracks in the grains. The endoscopic analysis revealed the weathering of the inclusions and their filling with iron oxides or clay minerals. This evolution explains why more than 15% of the grains had a rust color and why the greater the size the more pronounced the color was (25% rust color in the coarse sand but only five to 10% in the very fine sand).

The endoscopic and the exoscopic analysis identified some α prismatic quartz grains, indicating the sedimentary origin of part of the material (Plate 1, Picture 11). They represented less that 0.5% of the grains and were found mainly in the coarse fraction. These grains were not observed in the grey or yellow sandstones of the Phu Phan formation. However more than 95% of the xenomorphic quartz grains found in all the Quaternary deposits indicated a granitic or metamorphic origin.

Discussion

The particle size distribution, together with the morphoscopic, exoscopic, and endoscopic analyses prove the amazing homogeneity of all the materials studied, except for the Phu Phan formation, which differs entirely.

The homogeneity of the particle size distribution of the sand, whatever the material, evidences a common origin. The type of repartition of the size fractions, with a mode at 125 µm, is an indication of aeolian transportation, which agrees with the conclusions of Boonsener (1991). Although the value of the mode is higher than the values reported for hot deserts (Goude-Gaussen, 1990), medians between 63 and 125 µm have been indicated already by Mainguet (1996) in a periglacial Chinese loess.

The fact that most grains observed by morphoscopy were of the UE type and the fact that the RF were more frequent in the coarse sand is also an indication of aeolian transportation. The predominance, within the UE type, of grains smaller than 100 µm with blunt edges and aeolian marks, is another sign of aeolian transportation.

The many mechanical marks on the grain surface observed by exoscopy (cupules, crescent-shaped and V-shaped features) testify to the aeolian transportation of the materials and prove that the transportation was conducted under very high energy. Moreover, the sub-parallel friction traces and the crushing traces are factors that favor the argument of a periglacial climate during the transportation (Le Ribault, 1977; Goude-Gaussen, 1990). As some grains were affected by chemical polishing, minor hydric reorganizations after deposition are likely to have occurred.

The ubiquity of rhyolitic automorph quartz crystals revealed by endoscopy confirms the common origin of the materials (Clochiatti, 1975). As none of the bedrock in the region contains the same crystals, the materials must have been introduced from elsewhere. It would be interesting to compare the Thai aeolian sand with the loess of Sichuan province in southern China, where inclusions specific to rhyolitic formations may be found.

The Phu Phan is a Cretaceous formation that dominates the whole region, splitting the sedimentary basin into two sub-basins. The aeolian sand is deposited mainly at the foothills of this formation, where the present depth of the aeolian deposit is the greatest (more than five metres). This phenomenon could explain the weak slopes in the lowlands and the many meanders of the rivers. It could also explain the festooned, dendritic or fan shapes of the Quaternary deposits. However, it is surprising that during the subsequent evolution of the landscape, the materials of the Phu Phan formation did not combine with the aeolian sand to a point where they would become detectable.

The aeolian origin does not rule out a polishing of the grain in aquatic conditions before the final immobilization and the transformation into soils. Geographic observations (loess on the plateaus in the north of Sichuan province in China, strong northeasterly winds) suggest the probability of evolution by wind after the materials had been deposited. More research is needed however to determine the extension of the aeolian deposits in Southeast Asia. The description of "cover layers" in most countries, and even further south in Malaysia (Hoang Ngoc, 1989; 1994), suggests that the aeolian sands could have been deposited over a very wide area. Another research requirement is to spot the source of the materials brought by the wind and to determine the paleoclimate that triggered the process.

Conclusion

All the factors we studied converge to prove that most soils and Quaternary deposits of the Khon Kaen region were transported by the wind in periglacial conditions. The specific particle size distribution, the unusual environmental factors (UE dominant and presence of more RF in the coarse sands), the marks of impact on the surface of the grains, and the comminution by fragmentation of the sand grains under high energy provide a coherent series of clues. These materials are entirely different from the Phu Phan formation, which is much more ancient and with which they have no genetic links.

This study did not reveal any difference between the so-called high, middle and low terraces. Originally the distinction between high and low terraces was based on their respective elevation. The concept of terraces was not sufficient to explain how the topography was formed, how the soils developed, and how the soils are distributed over the landscape. As a consequence we suggest using the term "periglacial aeolian sand" for all the deposits of the Khon Kaen region formerly named high, middle, and low terraces.

A significant proportion of rhyolitic quartz was found, while no such quartz has been described in Northeast Thailand. This is proof that the deposit was transported over long distances, probably from China. However the high proportion of sand in the deposit challenges the possibility of transport by saltation over such a long distance. A comparison with the loess of southern China (Lu and Sun, 2000) should allow a better comprehension of how and when the aeolian sand of Southeast Asia was transported to the region. The work by Sanderson *et al.* (2001), who advocated using luminescence for the ageing of the sand grains of Northeast Thailand between 14,000 and 32,000 years, is a promising method for such a comparison.

Acknowledgments

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Annexe 2

Physical characteristics of sandy upland soils in Northeast Thailand related to soil formation and land use

Grégory Lesturgez, Emmanuel Bourdon, Roland Poss and Daniel Tessier

Caractéristiques physiques des sols sableux du Nord-Est Thaïlandais en relation avec la pédogenèse et l'usage des terres.

Les sols sableux du Nord-Est Thaïlandais sont souvent considérés comme problématiques du fait de leurs caractéristiques chimiques et physiques défavorables. De fortes densités apparentes et une résistance à la pénétration élevée sous l'horizon travaillé constitue en effet une contrainte majeure à la production agricole. Par ailleurs, les classes de sols sont très nombreuses dans la région et ont été établies en se focalisant sur l'usage des terres. L'organisation complexe de ces classes de sols à l'échelle du paysage rend la généralisation des études délicates. Dans la perspective d'une étude extensive de la dégradation physique des sols des hautes terres, les caractéristiques physiques d'une dizaine de sols représentatifs ont été étudiées en fonction de la classe, de la topographie ou encore de l'usage des terres. Les résultats ont montré que les sols se sont développés dans un matériau sableux très homogène et que la différenciation pédogénétique est principalement due à la redistribution de l'argile dans le profil. Les propriétés physiques défavorables ont été observées de façon systématique et indépendamment du type de sol ou de mise en valeur. Cependant, le taux d'argile semble être un facteur clef dans l'intensité du phénomène et suggère une sensibilité au tassement corrélée au taux d'argile.

Physical characteristics of sandy upland soils in Northeast Thailand related to soil formation and land use.

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Abstract

Sandy soils of Northeast Thailand are often considered as problem soils because of both chemical and physical unfavourable properties. High bulk density and soil strength under the tilled layer constitute a strong constrain for agriculture production. However, soils of the region range on a very large panel of soil series established with an interpretation for use purpose. The complex organisation at landform scale makes generalisation uncertain. In the perspective of studying soil physical degradation of sandy uplands, physical characteristics have been investigated as a function of soil series, topography and land use. Results shown that soils have developed in an homogenous sandy material and pedogenetic differentiation is mostly the result of clay redistribution. Adverse physical characteristics as dense layer were observed extensively and independently of soil series and land use. However, the clay content appeared as a key factor in the intensity of the phenomenon and suggested that sensitivity to compaction is related to clay content.

Introduction

Light textured sandy soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. Continuous production of crops such as rice, kenaf, cassava and sugarcane has resulted in a rapid decline in fertility, with an associated loss of productivity. In their pristine state these soils support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998).

These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 2 $cmol_c\ kg^{-1}$) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999). In addition unfavourable physical properties were mentioned in several studies as a main constraint to crop production in the region (Kheoruenromne and Suddhiprakarn, 1984; Sakurai *et al.*, 1996) and in particular, the presence of a dense and resistant layer at 20-40 cm depth hampering root elongation (Hartmann *et al.*, 1999; Bruand *et al.*, 2004).

Soils of the region range on a very large panel of soil series established with an interpretation for use purpose (Haimsrichat *et al.*, 1993). The numerous soil series appear on the soil map as a very complex patchwork which makes difficult generalisation of punctual studies. In the perspective of studying soil physical degradation of sandy uplands of Northeast Thailand, it appeared necessary to investigate at the landscape scale: (i) the physical characteristics of sandy soil and isolate similarities and disparities between soils ; (ii) the physical degradation as a function of physical properties and land uses.

Material and methods

Physiography of Northeast Thailand

Northeast Thailand, also called Korat Plateau, lies between longitudes 101-105°E and latitudes 14-18°N (Figure 1-a). The plateau is gently undulated and is delimited in the west and south respectively by Petchabun and Phanom Dongruk mountain ranges, and in the north and east by the Mekong river (Figure 1-b). The elevation ranges from 100 to 200 m and the land surface and the underlying rock formations slope gently inward to the centre of the plateau. (Yuvaniyama, 1999). The region can be divided into four major geographic units: the alluvial plains, plateaus, mountainous areas, and intra-mountainous areas (Miura *et al.*, 1990). The surface of the plateau is covered extensively with sandy materials, which rest on laterite layers (Mitsuchi *et al.*, 1986). This surface soil cover normally ranges in

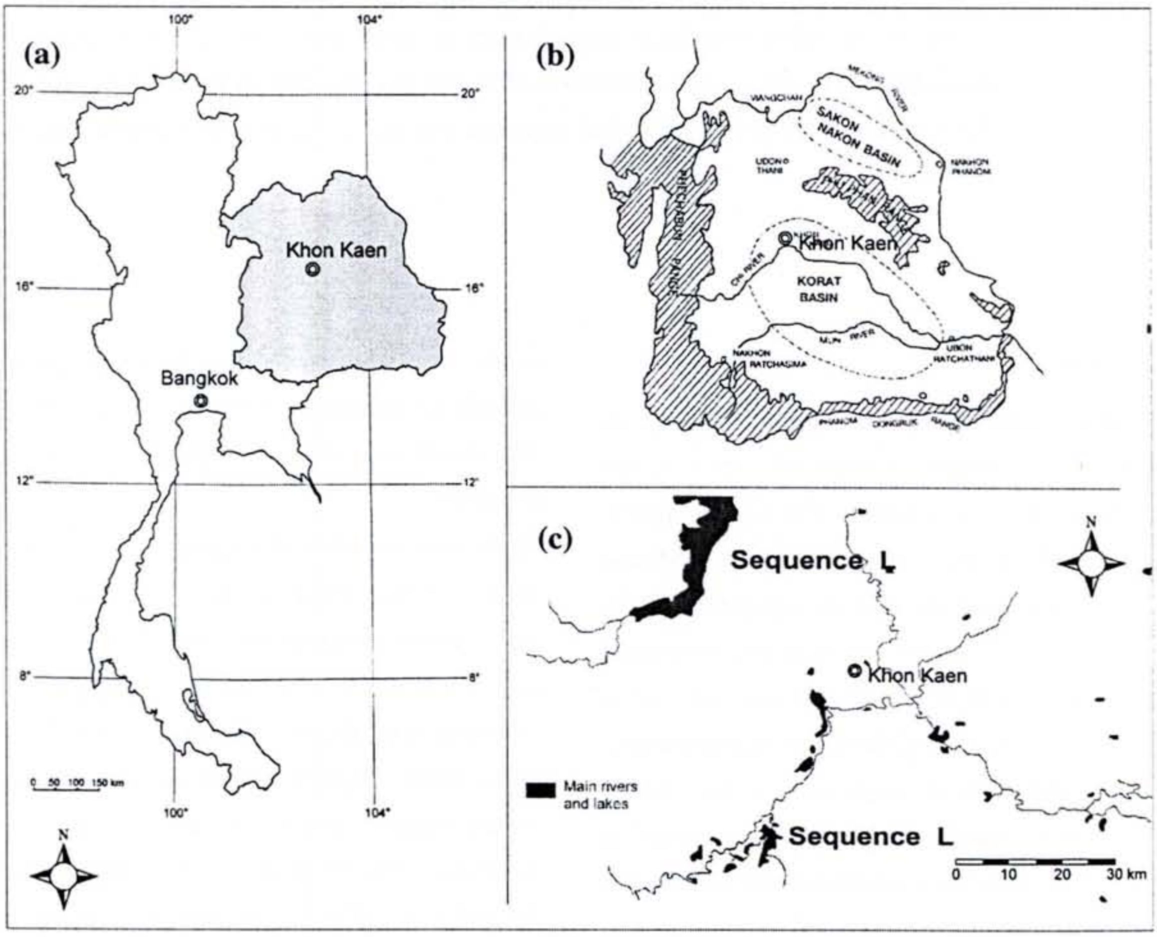

Figure 1: Geography (a) and physiography (b) of Northeast Thailand. Sequences location (c).

thickness from few metres to few decimetres in skeletal soil. The soil colour is varied ; red, red-yellow, brown and grey. Classification of soils depends chiefly on properties and thickness of this surface soil cover (Haimsrichat *et al.*, 1993).

Studied sequences

Two representative land forms have been chosen according to the landform and soil map. Sequences L and M (Figure 1-c) are related respectively to low and middle terrace according to Moorman *et al.* (1964). On each sequence, five soil profiles have been positioned ranging from the top to the lower part of the landform (Figure 2). For the first sequence (L1 to L5), profiles have been described under various land uses. At contrary, for the second sequence (M1 to M5), soil profiles have been described exclusively under sugarcane based crop systems.

Profile description and field measurements

In each position a pit was opened and a vertical face of 120 cm large and 150 cm height was described. Each soil horizon was characterised by dry and wet colours (Munsell Soil Colour Charts, 1975), structure, porosity, roots, biological activity and limit. Description has been conducted in order to be consistent with Thai soil classification (Imsamut and Boonsompoppan, 1999). Bulk density profiles were determined using 6 cylinders of non perturbed soil for each depth (10, 20, 30, 40, 50, 70 and 90 cm depth). Samples were dried at 105°C for 48h and volume of each cylinder was measured. Soil strength was estimated using a hand penetrometer on the vertical face of the pit (120×100 cm^2) using a 5 cm square grid. A conic head penetrometer was used and the resistance was quantified at field water content (dry season). Water content profiles were determined using 6 fresh soil samples (≈ 200 g per sample) each 10 cm just after penetration resistance measurement. Water content of each sample was determined by difference of fresh and dry weight (105°C / 48h). Bulk samples (≈ 500 g) were collected at each 10 cm increment down to 1 m from the pit face.

Particle size distribution

Bulk samples were air-dried and sieved to pass a 2-mm mesh before texture and sand size distribution was measured. Particle-size distribution was measured, after pretreatment with H_2O_2 and sodium hexametaphosphate,

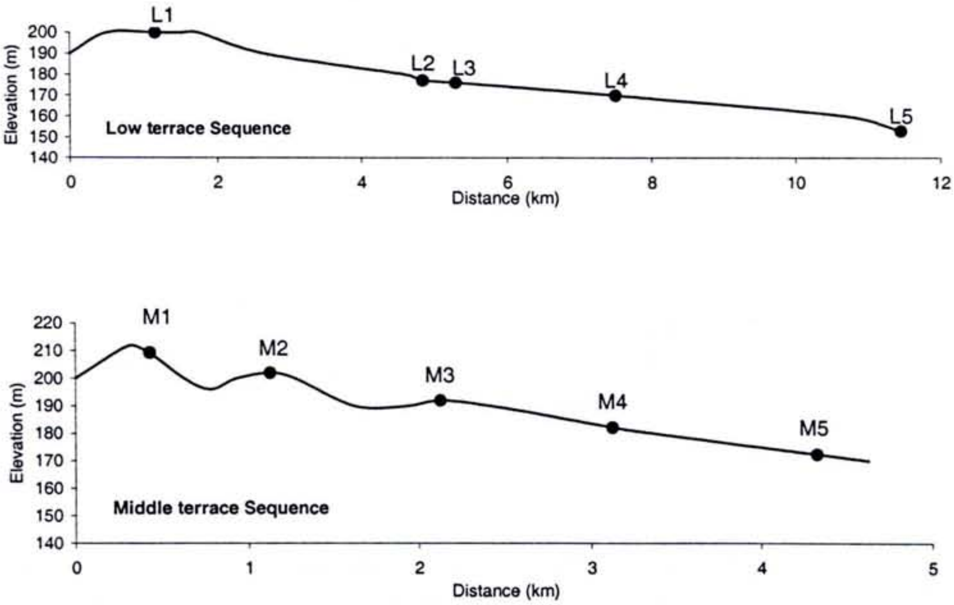

Figure 2: Repartition of the studied profiles on the two sequences

using the pipette method on 20-g samples and sand size distribution by sieving the cleaned sand fraction in a column of 16 sieves (AFNOR).

Results

Profile descriptions

All soil profiles were cultivated and therefore presented a tilled layer (Ap) darker than the rest of the profile. The depth of this layer, depending of the crop system and farmer practices, was variable but mainly confined to the top 25 cm of the profile. In profiles M1 and M4, this layer appeared clearly dissociated in two different horizons, corresponding respectively to a freshly tilled layer (Ap_1), and to an older and deeper tilled layer (Ap_2). Structure ranged from granular (after tillage) to massive. The lower limit of Ap was always clear, more or less wavy. Roots are mainly confined to this layer. Underneath, soil profiles looked quite heterogeneous especially because of the large range of colours but presented some similarities. Very few roots and no obvious earthworm activity under the Ap horizon. The upper part of the profile was usually lighter (E) and presented more or less a clear limit with the lower part (Bt).

Bulk density and soil strength

Bulk density and soil strength are presented as a function of depth for each profile (see tables under profiles descriptions). Bulk density ranged from 1.5 to 1.9 $Mg.m^{-3}$ and from 1.4 to 1.7 $Mg.m^{-3}$ respectively in sequence L and M. The tilled layer (Ap) presented always the lowest bulk density values while the highest values were usually found in the layer directly underneath, approximately between 20 and 40 cm depth. Soil strength was highly variable between profiles and absolute values are to consider together with soil moisture profiles (see tables). However, it is of note that soil strength was always higher in the dense layer previously mentioned compared to the upper and lower layers which presented comparable moisture contents. Also, soil strength had a tendency to increase with depth when the profile was dry (L4).

Clay distribution and texture

Clay (< 2 μm), silt (2-50 μm) and sand (50-2000 μm)

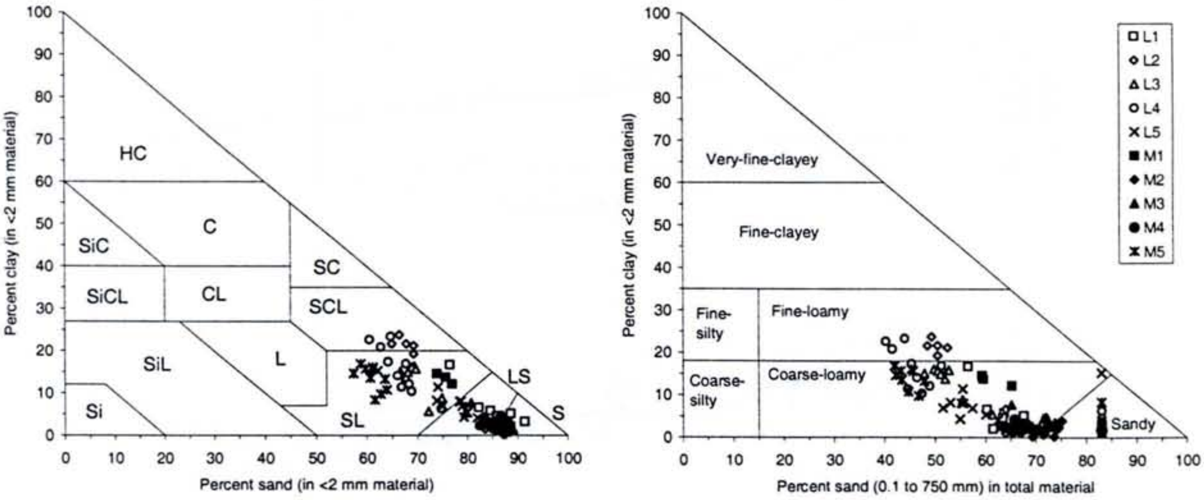

Figure 3: Repartition of studied soil in soil texture classes triangle (left) and family particle-size classes triangle (right). Abbreviations for the texture classes are HC, heavy clay; C, clay; SiC, silty clay; SiCL, silty clay loam; CL, clay loam; SC, sandy clay; SiL, Silt Loam; L, loam; SCL, sandy clay loam; SL, sandy loam; Si, silt; LS, loamy sand; S, sand.

fractions are presented as a function of depth for each profile (see tables under profiles descriptions). Clay content ranged from 1 to 24 % and from less than 1 to 17 % respectively in sequence L and M. Range of value was slightly higher for sequence L, but average value was drastically different (11 % in L compared to 5 % in M). With the exception of L5, clay content increased as a function of depth while silt content remained, on the whole, constant. Distribution of profiles in the texture classes triangle is presented in Figure 3-a. Soil samples from sequence L ranged in texture from sand (S) to sandy clay loam (SCL) while soil samples from sequence M ranged in texture from sand (S) to sandy loam (SL). Distribution of profiles in the particle-size classes is presented in Figure 3-b. In sequence L, soil samples were coarse loamy (L1, L3 and L5) or in between coarse and fine loamy (L2 and L4) when clay content was higher than 18 % in the subsoil. In sequence M, soil samples were exclusively coarse loamy material. M5 samples were typical coarse loamy materials while other profiles were positioned at the limit between coarse loamy and sandy materials. In both sequence, topsoil samples (0-10 cm) were sandy materials.

Sand size distribution

Sand size distribution was very homogeneous as a function of depth in all profiles. Figure 4 presents the sand size distribution measured in profile L4. There was no significant difference between depth (χ^2 tests). The distribution was unimodal (with a mode at 125 µm) and highlighted the high proportion of very fine sand (< 100 µm) and the quasi absence of grains larger than 400 µm. Profile L4 distribution is presented as an example, similar results were found in all profiles. Average sand size distributions of sequences L and M are presented in Figure 5. First, the confident intervals (5 profiles for each sequence) highlighted the homogeneity of sand size distribution between profiles within the same sequence. χ^2 tests revealed that there was no significant difference between the profiles of a same sequence. However the sand size distribution is slightly different between the two sequences. Sands were slightly coarser in the sequence M than in the sequence L. However, the proportion of very fine sand was still very important, the occurrence of grains larger than 400 µm was still very low and the mode was still centred on 125 µm (Figure 5).

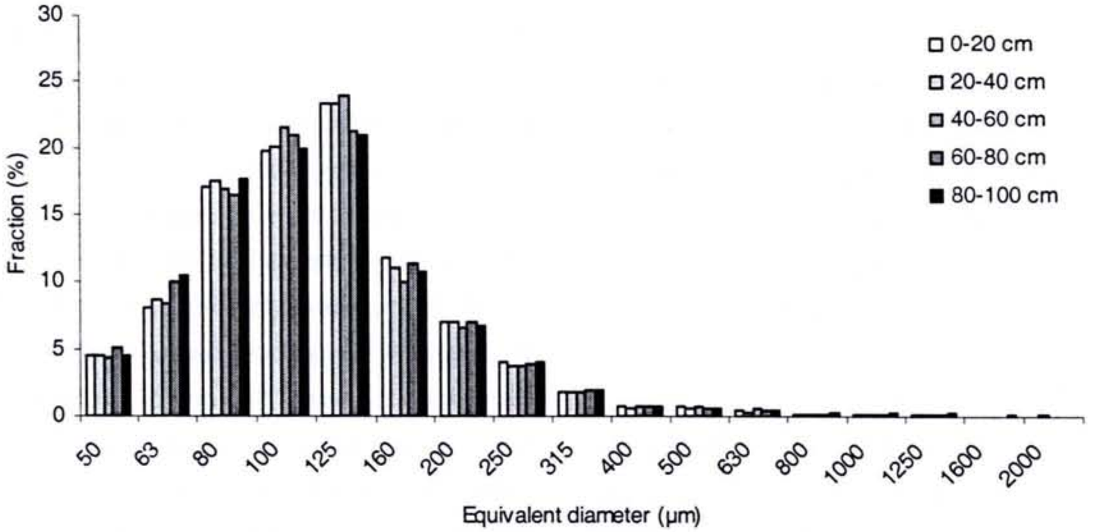

Figure 4: Sand size distribution as a function of depth in the profile L4.

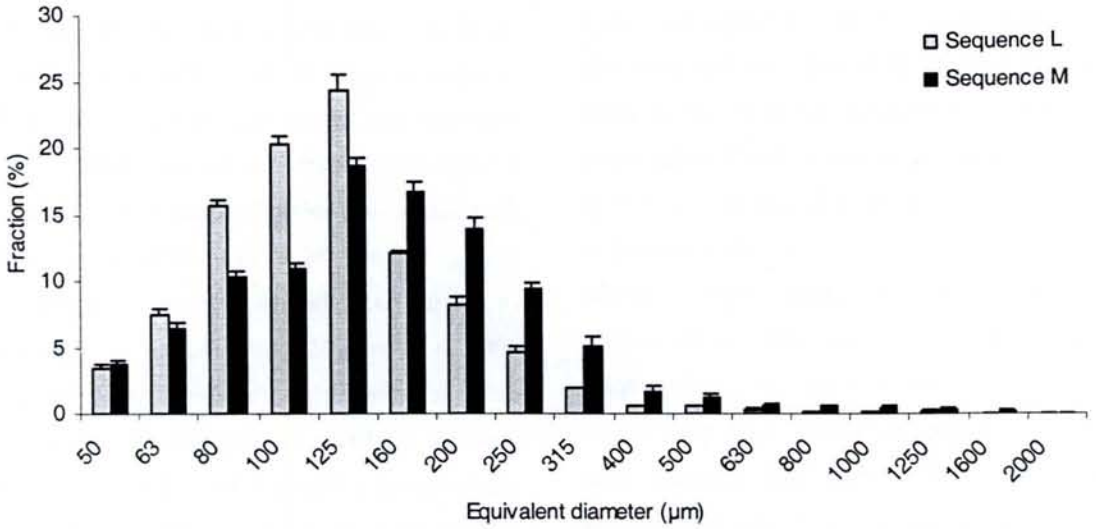

Figure 5: Sand size distribution measured in the two studied sequences. Each sequence include 5 profiles of 10 interval depths each (0-100cm). Means and confident interval (n=50, P<0.05).

Nature and morphology of sand grains

Main morphoscopic characteristics of sand grains from L4 profile are presented in Table 1. Sand grains are predominantly massive and elongated in shape, with in average 50 % in each. More than 85 % of the grains were transparent, translucent or opaque and less than 15 % of them were rust coloured. More than 2 thirds of the grains presented iron inclusions, and on average in the profile, half of them were strongly affected by breaks. Finally, more than 85 % of the grains are unworn (mainly evolved), meaning that they are mainly angular. These tendencies have been confirmed in other soil profiles of the two sequences and are regarded as general morphoscopic characteristics of the studied sandy soil. Observations using electron microscope (SEM) show that smaller quartz grains (silt and clay) exhibited common angular shapes and many breaks.

Mineralogy of the clay fraction

XRD patterns of the <2-µm fractions showed the presence of quartz, kaolinite and also 2:1 minerals at 14.5 Å in minor proportions. The presence of kaolinite is confirmed by comparing the XRD patterns of K and Mg saturated samples as the peaks at 7.37 Å and 3.57 Å disappeared upon heating to 520°C. Quartz represented a significant proportion of the <2-µm fractions. Observations using electron microscope (SEM) shown that small quartz had angular shape.

Discussion

Soil classification

Classification of soils of the plateau is based primarily on morphology, physico-chemical properties and thickness of the surface soil cover (Mitsuchi *et al.*, 1986). Sandy textured soils are classified as Quartzipsamments, that are further subdivided into *Nam Phong series* (nonaquic) and *Ubon series* (aquic). When the surface soil cover is thin and laterite layer appears within 50 cm of the surface, the soil are called *Phon Phisai series* (loose laterite), *Sakon series* (sheet laterite), *Phen series* (loose laterite, aquic) or *On series* (sheet laterite, aquic). The rest of the soils, i.e. non sandy, non-saline and non-lateritic soils fall mostly within the classes of Paleustults or Paleaquults. Paleustults are red to brown coloured upland soils, that are subdivided based on soil colour and texture. When soil colour is red (2.5 YR or redder), the soils are classed

	Shape (%)			Colour (%)						Environment (%)			
	Massive	Elongated	Hexagonal	Transparent	Translucent	Opaque	Rust	Inclusions (%)	Breaks (%)	Rounded Frosted	Blunt Shinny	Unworn Evolved	Unworn
0-15 cm	55	45	0	11	25	50	14	68	63	12	1	80	7
25-35 cm	73	27	0	24	56	10	10	71	35	10	4	84	2
40-50 cm	54	46	0	14	34	40	12	61	51	9	2	86	2

Table 1: Morphoscopic characteristics of quartz sand grains in L4 profile.

with *Yasothon series* (fine loamy) or *Chum Phuang series* (coarse loamy), when it is red-yellow, the soils are classed with *Warin series* (5 YR) or *Satuk series* (7.5 YR - 10 YR, chroma > 4), and when brown (7.5 YR - 10 YR, chroma ≤ 4) the soils go either to *Korat series* (fine loamy) or to *San Pa Tong series* (coarse loamy). Hydromorphic soils with grey matrix colour are classified with Paleaquults (e.g. *Roi Et series*) or Paleaqualfs (e.g. *Tha Tum series*).

This soil typology established in Northeast Thailand is well adapted to interpretation for land use (Haimsrichat *et al.*, 1993). However soil scientists currently faces difficulties in generalising results, as soil maps include a very complex patchwork of soil series. As soil series are defined on characteristics rather than soil processes, the genetic links between soils in a toposequence is not obvious. Some authors attempted to described organisation of soil series as a function of terrace level and topographic position (Wongwiwatchai and Paisancharoen, 1999) but in the two studied sequences, soils appeared more related to their micro-topographical situation than to a pedogenetic organisation on landforms (Figure 2).

Homogeneous sandy skeleton and clay distribution

The presence of an homogeneous sandy skeleton independently of depth (Figure 4) and through the different soils series and topographic position (Figure 5) is the first similarity between profiles to consider. This characteristic challenges both the concept of terraces and the alluvial origin of soils suggested by Moormann *et al.* (1964). Such homogeneous sandy skeleton is not common over large areas of alluvial deposits and the mode centred on 125 µm is more consistent with an aeolian origin as pointed out by Boonsener (1991). These results suggest that soil profiles from these two sequences, independent of them series, are formed from the same sandy material.

While sandy skeletons proved to be very homogeneous, clay content is highly variable with depth and from one profile to the next. Distribution of clay as a function of depth suggests intense leaching. Intensity of the phenomenon is probably related to the micro-topography. Leaching of clay may sometimes induce a smooth gradient when water table is deep (L4), sometime a clear limit when the water table stops the phenomenon in the first metre of profile (L2). On the other hand, soil profiles at the lowest position in the sequence may be influenced by lateral mobility of the clay. These hypothesis of soil formation are consistent with the constant size distribution of sand observed and with studies on clay translocations in the region (Boivin *et al.*, 2004).

Basically, the particle size family grouping were intended to allow groupings of soils that have a similar response to management, and to some extent, for engineering and related uses. In the particle-size classes, the limits of 18% clay between coarse and fine and loamy, reflect the change from non-plastic to plastic limit (US Soil Taxonomy). The distinction between fine and coarse loamy material is directly link to the clay content (more or less than 18 %). Therefore, this distinction between soil series is not relevant to identify soils as a function of parent material.

Bulk density and resistance to penetration

Bulk densities were high in all the studied soil (profiles descriptions tables) and are the results of assembling of sandy-silt-clay mixture where sands are very fine (Fiès and Stengel, 1981). The same concept of textural density of natural soils tends to explain also why bulk density values were on average higher in the sequence L than in the sequence M. Increases in bulk density with depth was also observed in some profiles and may revealed pedogenetic subsidence of the soils.

In and underneath the tilled layer, bulk density values are both the results of texture and of possible anthropic modifications of the soil structure. The presence of a denser layer at low depth (usually 20-40 cm) was noticed on all the studied profiles. These results are consistent with observations of several authors (Hartmann *et al.*, 1999; Imsamut and Boonsompoppan, 1999), suggesting that the dense layer is induced by cultivation but in absence of undeveloped reference (forest for example), densification cannot be attributed only to anthropic processes.

Agriculturally or naturally induced phenomenon, the presence of the dense layer is common independent of the clay content but the amount of clay seems to play a key role in the process of densification, resulting to more or less dense layer.

Dense layers presented high resistance to penetration as well as subsoils at the difference that dense layers are resistant even in moist condition when subsoils are loose in moist condition. Because of the natural density, the massive structure and the clay mineralogy (essentially kaolinite), sandy soils of northeast Thailand are subjected to hardsetting process (Mullins *et al.*, 1990). This induration process, which depends more on clay location in soil organisation than of its amount, may occur at any depth when the soil is dry. When the soil is wet, resistance to penetration related to hardsetting decreases considerably and becomes mainly the expression of friction between constituents. Clayey layers then appear less resistant probably due to the lubricant effect of clays material covering sand grains. Quartz grains which present considerable angularity need considerable energy to move one against the other, this energy increases when bulk density increase as we can see in the dense layers.

Conclusion

This studies highlighted several similarities and disparities between the main soil series occurring in the uplands of Northeast Thailand. First, sandy soils are composed of a homogeneous and fine sandy skeleton suggesting soils have developed from the same parent material. Both particle size and characteristics of the sand grains suggest also that this parent material is unlikely an alluvial deposit but more probably derived from aeolian activity. During pedogenesis, the homogeneous material has evolved to differentiated soil horizons as a function of clay redistribution in and between profiles. Depending on topographical and hydrological conditions, leaching has induced the various organisation of horizons commonly observed in the region. Physical degradation appeared to be extensively developed in cultivated areas, independently of soil type, physical characteristics and land uses. However, the intensity of the densification appeared well correlated with clay content. Since undeveloped reference site have not been studied yet and are not common even in the Thai soil taxonomy descriptions, the presence of the dense layer cannot be attributed only to human activities.

Acknowledgments

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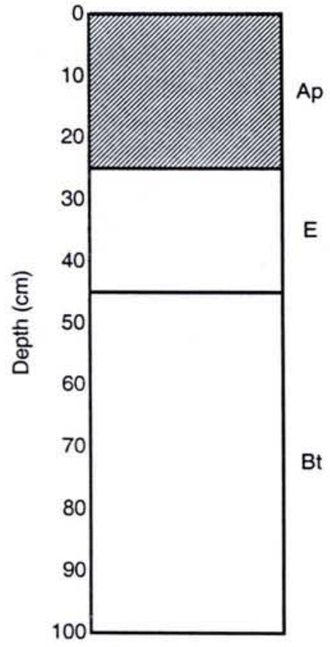
Profile L1

Location: N: 16°07'41'' ; E: 102°47'20''

Elevation: 200 m

Soil Series: Satuk series

The soil profile was located in a sugarcane field located at the top of the landform. Biological activity and especially termite activity is obvious on the soil surface. This land has been deforested some 40 years ago and cultivated mainly with cassava. sugarcane was introduced some 20 years ago and is now cultivated in rotation with cassava.



Ap (0-25) : Old tilled layer. Light reddish brown (5YR 6/4) to reddish brown (5YR 4/3). Sand to loamy sand, week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; high biological activity; clear wavy boundary.

E (25/45) : Pink (7.5YR 7/4) to brown (7.5YR 5/4). Sand; week fine and medium subangular blocky structure, massive; hard, friable, non sticky, non plastic; no roots; high biological activity; gradual smooth boundary.

Bt$_1$ (45-100+) : Strong brown (7.5YR 5/6) wet. Sand to loamy sand; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores;

Other : All the profile is streaked with darker horizontal volumes, they contain more clay and become hard when dry. Termites and roots are often found in this volume. The highest one is located at the bottom of the tilled layer.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	91.4	5.4	3.2	1.46	0.07	6.06	1.09	2.62	0.48
20	84.6	9.6	5.8	**1.55**	0.04	**8.97**	1.65	3.63	0.26
30	88.1	8.8	3.1	1.47	0.02	6.11	1.64	3.96	0.83
40	88.6	6.2	5.2	1.49	0.02	4.91	1.65	6.03	0.90
50	85.9	9.5	4.7	1.55	0.04	9.43	3.98	6.43	1.44
60	82.3	11.2	6.6			7.24	2.07	7.33	1.76
70	88.6	9.4	2.1	1.67	0.06	7.80	1.07	12.04	2.77
80	87.6	9.3	3.1			7.30	0.97	12.36	1.51
90	76.5	6.8	16.7	1.75	0.02	7.05	1.21	14.11	0.71
100	86.4	11.0	2.6			6.68	1.17	13.21	1.11

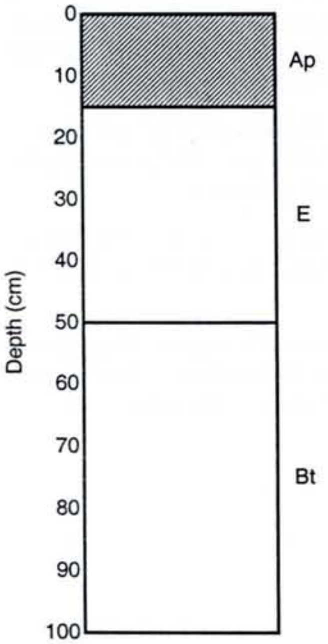
Profile L2

Location: N: 16°07'57'' ; E: 102°45'12''

Elevation: 177 m

Soil Series: Sapanthon-Korat series

The soil profile was located in a pasture, previously a paddy field, and located on the middle of the sequence. Vegetation comprised *gramineae* and herbaceous species. Biological activity is not obvious on the soil surface. The land has been deforested some 40 years ago and cultivated with rice until the last decade. Then it was converted to pasture as the soil is to hard for uplands crops but to permeable for rice, the farmer said.



Ap (0-15) : Old tilled layer. Light brown (7.5YR 6/4) to brown (7.5YR 4/2). Sand, week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; high biological activity; clear wavy boundary.

E (15-50) : Pink (7.5YR 7/4) to brown (7.5YR 5/4). Sand to loamy sand; week fine and medium subangular blocky structure, massive; hard, friable, non sticky, non plastic; no roots; high biological activity; gradual smooth boundary.

Bt$_1$ (50-100+) : Pink (7.5YR 7/4) to reddish yellow (7.5YR 6/6). Sandy clay loam; week fine and medium subangular blocky structure; soft, friable, sticky, plastic; no roots; few macropores;

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	87.5	9.7	2.8	1.52	0.01	19.68	4.32	1.43	0.49
20	86.8	11.1	2.1	1.59	0.02	25.48	5.55	1.51	0.43
30	87.5	11.5	1.0	1.55	0.03	17.82	4.29	0.87	0.43
40	83.5	15.0	1.5	1.56	0.03	9.17	1.24	1.43	0.50
50	80.1	13.3	6.6	1.64	0.08	12.31	3.51	4.51	1.05
60	69.3	11.5	19.3			20.23	4.78	7.33	0.64
70	64.9	13.4	21.7	1.68	0.03	19.49	4.03	9.51	1.21
80	66.4	9.8	23.8			13.79	2.64	10.93	0.74
90	67.8	10.6	21.7	1.66	0.06	7.59	1.08	12.29	1.62
100	69.3	9.5	21.2			5.61	0.60	11.47	1.85

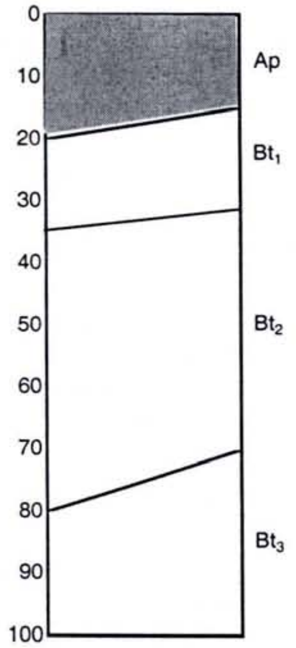
Profile L3

Location: N: 16°08'04'' ; E: 102°44'56''

Elevation: 176 m

Soil Series: Warin-Satuk series

The soil profile is located in a paddy field approximately at the middle of the sequence. The field is at the foot of a road and a railway. Rice has been harvest and the field is now a pasture. Biological activity is obvious on the soil surface with many earthworms turricules. The land has been deforested some 40 years ago and cultivated with rice until now.



Ap (0-15/20) : Old tilled layer. Very pale brown (10YR 7/3) to brown (10YR 4/3). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; high biological activity; clear wavy boundary.

E (15/20-32/35) : Light grey (10YR 7/2) to dark greyish brown (10YR 4/2). Sandy loam; week fine and medium subangular blocky structure, massive; hard, friable, non sticky, non plastic; no roots; high biological activity; gradual wavy boundary.

Bt$_1$ (32/35-70/80) : Reddish yellow (7.5YR 6/6) to brown (7.5YR 4/4). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores; few iron-manganese concretions; gradual boundary.

Bt$_2$ (70/80-100+) : Pink (5YR 7/4) to light brown (7.5YR 6/4). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores.

L3	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	72.2	22.2	5.7	1.61	0.04	**22.30**	4.64	2.66	0.44
20	79.6	15.0	5.4	**1.91**	0.08	**23.45**	3.09	4.69	1.36
30	74.9	16.3	8.8	**1.88**	0.10	**19.99**	3.13	8.48	1.61
40	69.3	14.8	15.9	**1.76**	0.07	9.26	1.58	8.79	1.15
50	67.7	18.5	13.8	1.70	0.08	4.46	0.47	11.87	0.38
60	66.6	18.3	15.1			2.98	0.42	12.01	1.08
70	69.4	14.2	16.4	1.71	0.04	2.35	0.25	14.29	1.08
80	68.9	14.9	16.1			1.76	0.23	17.26	0.45
90	69.7	14.6	15.7	1.70	0.02	1.21	0.15	16.67	2.14
100	68.1	17.0	14.9			1.07	0.12	22.32	1.12

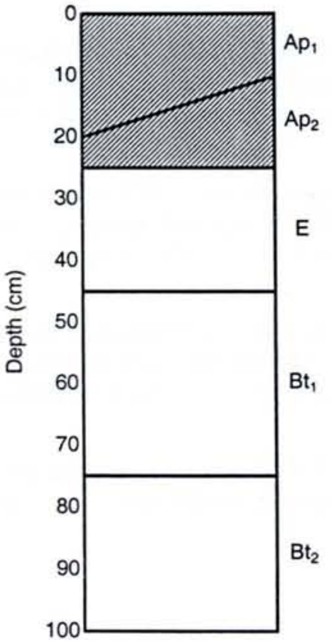
Profile L4

Location: N: 16°08'54'' ; E: 102°43'59''

Elevation: 170 m

Soil Series: Satuk-Korat series

The soil profile is located in a sugarcane field in the lower part of the landform. The land was deforested some 40 years ago and cultivated with rice until sugarcane was introduced 20 years ago. Sugarcane is now cultivated as a monoculture (3 year cycles) and heavy mechanisation has been used for the last decade.



Ap_1 (0-10/20) : Freshly tilled layer. Dark greyish brown (10YR 4/2) to very dark greyish brown (10YR 3/2). Sandy loam; week fine and medium subangular blocky structure, massive; soft, friable, non sticky, non plastic; many very fine and fine roots; clear wavy boundary.

Ap_2 (10/20-24) : Older tilled layer. Pale brown (10YR 6/3) to brown (10YR 4/3). Sandy loam; week fine and medium subangular blocky structure; massive and hard, friable, non sticky, non plastic; common roots, depth of planting; clear smooth boundary.

E (24-40/47) : Yellowish brown (10YR 5/4) to dark yellowish brown (10YR 4/4). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; no macropores; gradual wavy boundary.

Bt_1 (47-75) : Reddish yellow (7.5YR 6/6) to brown (7.5YR 5/4). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores; gradual boundary.

Bt_2 (75-100+) : Reddish yellow (7.5YR 7/6) in wet,. Sandy clay loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; common macropores; few iron-manganese concretions. Very cohesive when drying.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	74.7	19.0	6.3	1.61	0.13	10.23	3.05	7.62	0.71
20	68.8	20.8	10.4	1.75	0.04	**21.96**	4.88	6.84	0.68
30	68.3	19.5	12.1	1.69	0.04	**20.25**	3.98	6.58	1.23
40	66.8	21.8	11.4	1.69	0.05	**13.06**	2.54	10.06	2.06
50	66.0	19.8	14.1	1.67	0.02	9.34	1.77	7.06	1.92
60	67.7	15.4	16.9			9.18	1.43	7.94	1.39
70	64.2	18.4	17.4	1.74	0.05	12.06	2.28	8.19	0.92
80	62.7	16.4	20.9			17.40	2.59	8.57	0.77
90	64.7	12.0	23.4	1.76	0.08	**25.45**	6.78	9.02	1.11
100	60.5	16.8	22.7			**31.75**	8.21	9.70	1.83

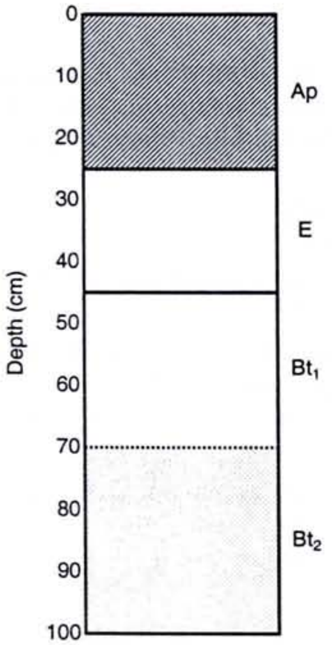
Profile L5

Location: N: 16°08'33'' ; E: 102°42'12''

Elevation: 153 m

Soil Series: Roi Et series

The soil profile is located in a pasture previously a paddy field. The pasture is located at the lowest point of the sequence, near a lake which partially flood the land at the end of rainy season. Vegetation is composed of *gramineae* and herbaceous species. Biological activity is not obvious at the soil surface. The land was deforested 40 years ago.



Ap (0-22/25) : Old tilled layer. Greyish brown (10YR 5/2) to dark brown (10YR 3/3). Sandy loam; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; clear wavy boundary.

E (22/25-40/50) : Light brownish grey (10YR 6/2) to dark greyish brown (10YR 4/2). Loamy sand; week fine and medium subangular blocky structure, massive; hard, friable, non sticky, non plastic; no roots; no macropores; gradual wavy boundary.

Bt$_1$ (40/50-70) : Reddish yellow (7.5YR 6/6) to brown (7.5YR 5/4). Loamy sand; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores; few soft iron-manganese concretions; gradual boundary.

Bt$_2$ (70-100+) : Light reddish brown (5YR 6/4) wet, common darker volume (7.5YR 5/6). Loamy sand to sand; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; few macropores; common soft iron-manganese concretions.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	62.2	22.5	15.3	1.56	0.07	7.45	1.54	6.68	1.13
20	74.1	14.5	11.4	**1.71**	0.05	**17.88**	4.64	**7.79**	1.95
30	78.7	13.3	8.1	**1.74**	0.05	**25.48**	4.36	**7.04**	1.28
40	78.4	13.6	8.0	**1.72**	0.05	**10.52**	2.12	**7.62**	2.15
50	78.9	14.2	6.9	1.62	0.03	3.72	0.50	9.31	1.07
60	79.3	16.4	4.3	1.61	0.03	2.57	0.21	8.31	1.36
70	79.9	14.7	5.3	1.59	0.04	2.91	0.27	10.77	0.68
80	82.0	13.9	4.1	1.68	0.04	3.46	0.35	10.95	0.76
90	73.9	17.9	8.2	**1.71**	**0.10**	3.69	0.46	10.58	3.20
100	75.0	18.1	7.0			3.71	0.42		

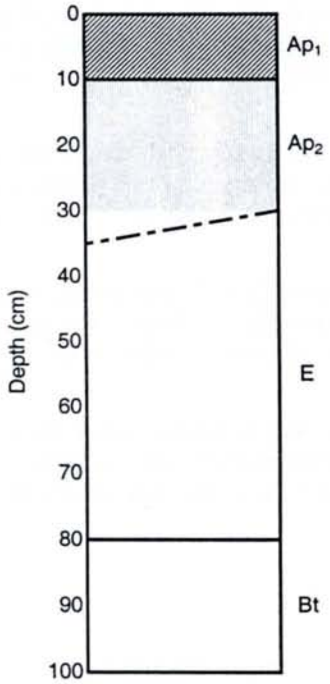
Profile M1

Location: N: 16°36'57'' ; E: 102°47'45''

Elevation: 209 m

Soil Series: Nam Phong-Chumpung series

Profile was described in a sugarcane field near the top of the landform (elevation max. 212 m). The land was deforested 40 years ago and cultivated with cassava and sugar cane until now.



Ap$_1$ (0-10) : Freshly tilled layer. Light brownish grey (10YR 6/2) to dark brown (10YR 3/3). Sand to loamy sand, granular structure; soft, friable, non sticky, non plastic; many very fine and fine roots; biological activity not obvious; clear wavy boundary.

Ap$_2$ (10-30/35) : Older tilled layer. Pale brown (10YR 6/3) to brown (10YR 4/3). Sand to loamy sand, granular to fine subangular blocky structure, massive, hard; soft, friable, non sticky, non plastic; many very fine and fine roots; high biological activity (termites); gradual wavy boundary.

E (30/35-80) : Very pale brown (10YR 7/4) to light yellowish brown (10YR 6/4). Sand to loamy sand; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; high biological activity; gradual smooth boundary.

Bt (80-150+) : Red (2.5YR 5/8 to 4/6). Sandy loam; week fine and medium subangular blocky structure; indurated, sticky, plastic; no roots; few macropores; This layer is very perturbed by termite activity.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	85.4	12.4	2.2	1.41	0.03	0.79	0.26	1.59	0.88
20	85.1	11.8	3.1	1.49	0.05	2.88	0.75	2.66	0.19
30	87.4	10.0	2.6	1.54	0.03	5.45	0.75	3.22	0.44
40	87.5	10.4	2.0	1.51	0.03	4.86	0.57	3.50	0.38
50	85.4	13.0	1.5	1.50	0.03	3.27	0.45	3.90	0.28
60	85.8	12.1	2.0			2.27	0.21	4.66	0.25
70	84.7	12.7	2.5	1.50	0.01	1.91	0.19	5.16	0.38
80	76.9	10.9	12.2			2.15	0.30	6.21	0.64
90	75.6	10.7	13.8	1.58	0.08	2.72	0.45	7.60	1.27
100	73.9	11.6	14.6			3.02	0.33	9.31	1.19

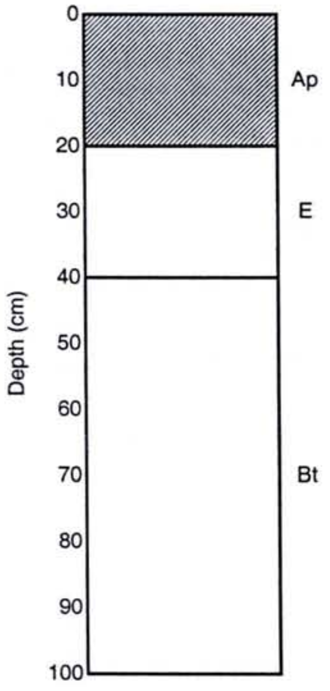
Profile M2

Location: N: 16°36’35’’ ; E: 102°48’05’’

Elevation: 202 m

Soil Series: Nam Phong series

Profile was described in a sugarcane field. The land was deforested 40 years ago and cultivated with cassava and sugar cane until now.



Ap (0-20/30) : Tilled layer. Very pale brown (10YR 7/3) to brown (10YR 5/3). Sand, granular to fine subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; biological activity not obvious; clear wavy boundary.

E (20/30-40) : Very pale brown (10YR 7/3) to light yellowish brown (10YR 6/4). Sand; week fine and medium subangular blocky structure, massive, hard; soft, friable, non sticky, non plastic; no roots; high biological activity; gradual smooth boundary.

Bt (40-150) : Very pale brown (10YR 7/4) wet. Sand; week fine and medium subangular blocky structure; indurated, sticky, plastic; no roots; few macropores; This layer is very perturbed by termite activity. Very clear limit.

C (150+) : Iron stone in sheet, continuous and very resistant. Iron stone developed in a gravel bed.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	88.2	10.1	1.7	1.49	0.06	2.00	0.37	1.74	0.32
20	88.6	10.6	0.8	1.52	0.03	3.17	0.53	2.33	0.30
30	86.9	11.5	1.5	1.53	0.03	5.60	0.76	2.60	0.31
40	87.0	10.9	2.1	1.51	0.02	4.62	0.79	3.23	0.41
50	87.2	12.6	0.3	1.47	0.03	3.06	0.34	3.56	1.15
60	87.5	12.2	0.3			3.19	0.38	3.93	0.60
70	86.8	9.3	3.9	1.50	0.06	3.01	0.50	5.55	0.98
80	85.7	13.0	1.3			1.87	0.23	5.28	0.72
90	87.1	10.6	2.3	1.56	0.05	2.04	0.24	6.47	0.35
100	88.1	9.1	2.9			1.88	0.24	6.24	1.31

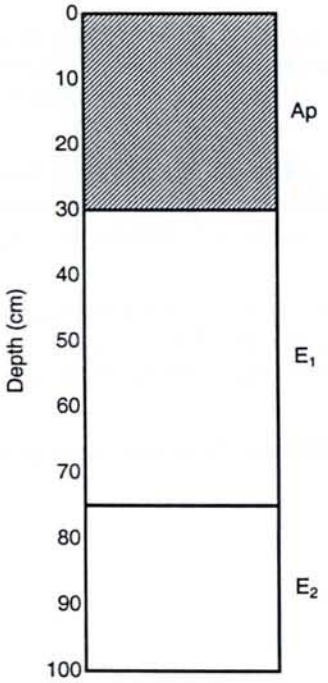
Profile M3

Location: N: 16°37'05'' ; E: 102°48'22''

Elevation: 192 m

Soil Series: Nam Phong series

Profile was described in a sugarcane field. The land was deforested 40 years ago and cultivated with cassava and sugar cane until now.



Ap (0-30) : Tilled layer. Pale brown (10YR 6/3) to brown (10YR 4/3). Sand to loamy sand, granular to fine subangular blocky structure, massive aspect; soft, friable, non sticky, non plastic; many very fine and fine roots; biological activity (termites); clear wavy boundary.

E$_1$ (30-75) : Very pale brown (10YR 7/3) to light yellowish brown (10YR 6/4). Sand to loamy sand; week fine and medium subangular blocky structure, massive, hard; soft, friable, non sticky, non plastic; no roots; biological activity (termites); gradual smooth boundary.

E$_2$ (75-120+) : Light yellowish brown (10YR 6/4) wet. Sand to loamy sand; week fine and medium subangular blocky structure; indurated, sticky, plastic; no roots; few macropores; biological activity (termites).

C (190+) : Iron stone in sheet, continuous and very resistant. Iron stone developed in a gravel bed.

M3	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	89.1	9.5	1.4	1.44	0.08	2.25	0.41	0.96	0.31
20	87.0	8.2	4.7	1.44	0.05	2.38	0.56	1.21	0.34
30	86.2	9.3	4.5	1.50	0.10	3.38	0.76	1.69	0.62
40	85.8	11.0	3.2	1.48	0.07	5.94	1.24	1.60	0.32
50	85.7	11.4	2.9	1.46	0.07	6.95	1.34	1.35	1.40
60	86.8	10.6	2.6			9.29	3.60	2.67	0.66
70	87.5	8.9	3.6	1.45	0.08	9.38	2.82	2.92	0.67
80	87.4	10.0	2.6			9.08	2.71	3.15	1.26
90	84.7	12.8	2.5	1.52	0.11	6.93	2.55	4.00	1.33
100	80.8	11.5	7.7			4.04	0.83	6.03	4.22

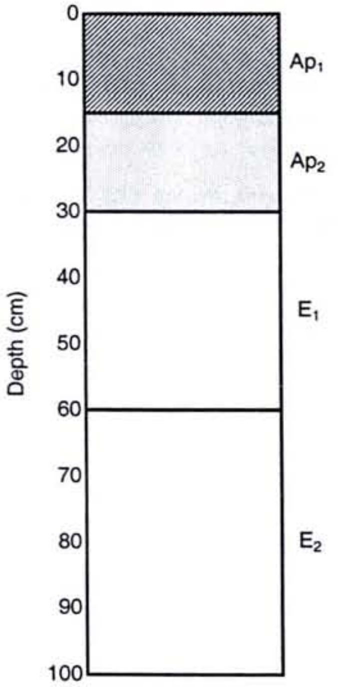
Profile M4

Location: N: 16°36'24'' ; E: 102°48'06''

Elevation: 182 m

Soil Series: Nam Phong series

Profile was described in a sugarcane field. The land was deforested 40 years ago and cultivated with cassava and sugar cane until now.



Ap$_1$ (0-15) : Freshly tilled layer. Brown (10YR 4/3). Sand to loamy sand, granular to fine subangular blocky structure; soft, friable, non sticky, non plastic; many very fine and fine roots; biological activity (termites); clear wavy boundary.

Ap$_2$ (15-30) : Older tilled layer. Pale brown (10YR 6/3) to brown (10YR 4/3). Loamy sand, granular to fine subangular blocky structure, massive aspect; soft, friable, non sticky, non plastic; few fine roots; hard, clear wavy boundary.

E$_1$ (30-60) : Very pale brown (10YR 7/3) to light yellowish brown (10YR 6/4). Sand to loamy sand; week fine and medium subangular blocky structure; soft, friable, non sticky, non plastic; no roots; biological activity (termites); gradual smooth boundary.

E$_2$ (60-120+) : Reddish yellow (7.5YR 6/4) wet. Loamy sand; week fine and medium subangular blocky structure; indurated, sticky, plastic; no roots; few macropores; biological activity (termites).

C (220+) : Iron stone in sheet, continuous and very resistant. Iron stone developed in a gravel bed.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	85.2	13.1	1.7	1.44	0.05	0.87	0.15	3.54	1.15
20	87.1	10.3	2.6	1.50	0.06	1.57	0.33	2.26	0.35
30	85.9	12.6	1.5	1.51	0.02	2.28	0.35	2.86	0.35
40	86.5	11.9	1.6	1.50	0.02	1.92	0.23	3.56	0.42
50	83.4	12.4	4.2	1.47	0.04	2.08	0.23	4.31	0.48
60	83.0	14.6	2.4			1.83	0.29	5.54	0.71
70	82.4	15.4	2.3	1.47	0.03	1.56	0.22	5.36	0.30
80	85.5	12.7	1.8			1.91	0.20	5.75	0.23
90	84.3	13.5	2.3	1.57	0.03	2.18	0.22	6.76	0.21
100	83.5	14.0	2.5			2.42	0.24	7.71	0.20

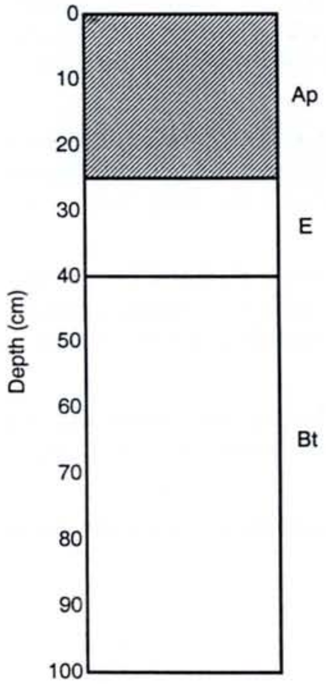
Profile M5

Location: N: 16°37'11'' ; E: 102°49'35''

Elevation: 172 m

Soil Series: Roi Et series

Profile was described in a sugarcane field near the bottom of the landform. The land was deforested recently (less than 10 years). The soil was hydromorphic and much clayey than the top and middle of the sequence. Fields nearby are cultivated with rice.



Ap (0-25) : Freshly tilled layer. Light yellowish brown (10YR 6/4) to dark yellowish brown (10YR 4/4). Sandy loam, fine subangular blocky structure, non sticky, plastic; many very fine and fine roots; clear wavy boundary.

E (25-40) : Very pale brown (10YR 7/3) to dark yellowish brown (10YR 4/4). Sandy loam, fine subangular blocky structure, massive aspect, sticky, plastic; no roots; gradual smooth boundary.

Bt (40-120+) : Pink matrix (5YR 7/3) with many reddish yellow stairs (7.5YR 7/8). Sandy loam, fine subangular blocky structure, non sticky, plastic. No roots, few macropores.

	Particle size distribution (%)			Bulk density (Mg.m^{-3})		Soil Strength (kg.cm^{-2})		Moisture (%)	
Depth (cm)	Sand	Silt	Clay	Means	Std.	Means	Std.	Means	Std.
10	61.6	30.1	8.4	1.47	0.07	5.78	1.99	4.94	0.53
20	62.7	27.5	9.8	1.58	0.06	14.45	2.78	5.40	0.39
30	63.9	25.3	10.8	1.70	0.07	30.33	7.28	4.84	0.19
40	63.6	23.2	13.3	1.60	0.06	29.82	6.01	5.77	0.34
50	60.7	25.8	13.5	1.62	0.05	19.68	3.17	6.31	0.28
60	61.2	23.2	15.6			16.16	2.52	6.87	0.35
70	59.7	24.6	15.7	1.66	0.03	15.63	2.81	9.69	2.69
80	61.1	22.7	16.1			15.43	2.58	8.51	0.99
90	58.8	24.3	16.9	1.68	0.03	10.22	1.42	9.28	1.25
100	57.4	28.0	14.6			7.77	1.56	11.17	1.03

Annexe 3

Origin of compaction in sandy soils of Northeast Thailand: A comparison between forest and cultivated soils

Grégory Lesturgez , Christian Hartmann, Sawaeng Ruaysoongnern, Daniel Tessier & Roland Poss

Origine du tassement dans les sols sableux du Nord-Est Thaïlandais : Une comparaison entre forêt et sols cultivés.

Le tassement des sols et les dégradations induites deviennent de plus en plus importantes de par le monde et remettent en cause le mode de gestion actuelle des terres. Dans le Nord-Est Thaïlandais, des dégradations des sols telles que l'acidification et l'appauvrissement chimique ont été mises en évidence. La présence généralisée d'un horizon dense à faible profondeur dans les sols sableux a été observée mais son origine anthropique n'a pas été prouvée. Trois Acrisol ont été mis en valeur il y a environ 40 ans et cultivés de façon intensive jusqu'à ce jour. Les propriétés physiques des sols des zones cultivés ont été comparées à celle des sols des forêts adjacentes de manière à quantifier l'impact de l'agriculture intensive. L'étude a montré que la présence d'un horizon dense entre 20-40 cm est le résultat de la mise ne culture. Le tassement a induit une organisation nouvelle de la phase solide, avec une structure massive et très peu de macropores. Ces changements induisent quant à eux de très fortes résistances à la pénétration dans l'horizon dense. La distribution de l'argile dans le profile semble également avoir été influencée par la mis en culture. Une augmentation générale du taux d'argile dans l'un des profils suggère la micro-fracturation des grains de quartz.

Origin of compaction in sandy soils of Northeast Thailand: A comparison between forest and cultivated soils

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Abstract

Soil compaction and related land degradation are becoming more important worldwide and are challenging the concept of sustainability of current land management systems. In Northeast Thailand soil degradation comprises of acidification and chemical impoverishment have been highlighted but the presence of a compact layer in the topsoil of most sandy soils has not proved to be induced by cultivation. Three Acrisol cleared of dipterocarp forest 40 years ago were used for continuous crop production. Their physical properties have been compared with adjacent undisturbed forests in order to quantify the main changes induced by intensive agriculture. The study showed that the presence of the compact layer located at 20-40 cm depth was the result of cultivation. Compaction resulted in a new organisation of the solid phase with a massive structure and very few macropores. These changes result in a high soil strength in the compact layer. Distribution of clay in the profile appeared to be influenced by land use. An increase of the clay fractions was also observed in one site and attributed to breaking of quartz grains.

Introduction

Light textured sandy soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. Continuous production of crops such as rice, kenaf, cassava and sugarcane has resulted in a rapid decline in fertility, with an associated loss of productivity. In their pristine state these soils support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 2 $cmol_c$ kg^{-1}) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999). Soils of the region are therefore often considered problem soils and the degradation is assumed to be anthropogenic. Since the reference soil profiles are mainly described under cultivated area (Imsamut and Boonsompoppan, 1999), there are no evidence that adverse characteristics of the soils are all induced by cultivation. Noble *et al.* (2000) assessed the chemical degradation using a cation exchange index and highlighted that intensive cultivation resulted in a strong acidification and impoverishment of the soil resource. However the origin of adverse soil physical properties as presence of a compact layer hampering root growth (Hartmann *et al.*, 1999) and high soil strength organisation of the soil (Bruand *et al.*, 2004) need to be clarified. A paired site study has been conducted in order to investigate physical changes following deforestation and intensive cultivation of sandy soils.

Table 1: Selected properties for the three studied sites (forest and adjacent cultivated areas).

			Particle size distribution (%)				Bulk density
Horizon	Depth (cm)	Colour (dry)	Sand	Silt	Clay	pH	$Mg.m^{-3}$
Site 1 (Satuk soil serie) : Forest							
A	0-15		82.1	16.4	1.5	5.6	1.4
E	15-60		82.2	15.6	2.1	5.3	1.5
B1	60-120+		69.5	14.1	16.4	5.1	1.4
Site 1 (Satuk soil serie): Cultivated area							
Ap	0-30		83.8	15.6	0.5	4.6	1.6
E	30-60		76.1	15.8	8.0	4.6	1.7
B1	60-120+		71.8	13.1	14.9	4.8	1.5
Site 2 (Yasothon soil serie): Forest							
A	0-15		65.9	30.2	3.9	6.0	1.4
E	15-60		71.2	21.4	7.5	5.4	1.6
B1	60-120+		65.7	18.0	16.5	5.4	1.5
Site 2 (Yasothon soil serie): Cultivated area							
Ap	0-25		75.0	22.4	2.6	5.2	1.6
E	25-60		70.1	21.0	9.0	5.1	1.7
B1	60-120+		66.8	18.7	14.8	4.9	1.4
Site 3 (Warin soil serie): Forest							
A	0-15		78.7	18.4	2.7	5.4	1.4
E	15-65		74.9	18.0	7.0	5.2	1.4
B1	65-120+		67.9	15.3	16.5	4.9	1.5
Site 3 (Warin soil serie): Cultivated area							
Ap	0-15		80.5	16.8	2.7	4.6	1.6
E	15-60		71.2	16.9	11.9	4.8	1.6
B1	65-120+		64.0	15.1	20.7	4.6	1.5

Material and methods

Field sites

A paired site approach was conducted to quantify differences between the dipterocarp forest (undeveloped) and agricultural (developed) areas. The selection of the sites was based on the following criteria: (i) the same soil type in both areas with little topographical differences (i.e. slope) between the two areas (ii) the existence of an undisturbed dipterocarp forest in close proximity to an agricultural field of known history during the period under production; (iii) a well-defined boundary separating the two land use systems;

The three paired sites are:

- Site 1: Satuk soil series (N 16°48' ; E 102°51'): Dipterocarp forest and adjacent cultivated area that was deforested 30 years ago and cultivated with cassava and sugar cane until now.
- Site 2: Yasothon soil series (N 16°39' ; E 102°54'): Dipterocarp forest and adjacent cultivated that was deforested 40 years ago and cultivated with cassava, sugar cane until productivity declined. Since fertility is considered too low, it is cultivated with lemon grass.
- Site 3: Warin soil series (N 16°16' ; E 102°47'): Dipterocarp forest and adjacent cultivated that was deforested 40 years ago and cultivated with cassava and sugar cane until now.

Their selected characteristics are presented in Table 1.

In each of the three sites, two pits were opened respectively in the forest and in the adjacent cultivated area. Paired profiles were about 30 m apart. Spatial variation in soil nature and compaction (for the cultivated area) were check respectively with auger and surface penetrometer in the area before opening the pits.

Field measurements and sampling

For each pit, major soil characteristics (colour, hand texture, roots, biological activity) were described on the face of the pit. Resistance to penetration was then measured using a pocket cone penetrometer on the 1×1 m^2 face with a grid of 5-cm. Five 200-g samples were collected at 10 cm intervals to a depth of 1 m and a gravimetric water content profile was obtained by oven-drying the samples (105°C, 48h). The profile was cleaned and dry bulk density was measured by the cylinder method. Five cylinders were taken at10 cm intervals to a depth of 1 m and oven-dried (105°C, 48h). Undisturbed samples ($12\times12\times8$ cm^3) were collected in the Ap (5-15 cm), E (25-35 cm) and Bt horizons (60-70 cm) for cultivated profiles and at the same respective depths in the adjacent forests. Bulk samples were taken at 10 cm intervals to a depth of 1 m. These samples were collected on a 1-m horizontal line in order to integrate spatial variability.

Laboratory measurements

Bulk samples were air-dried and sieved to pass a 2-mm mesh before pH, texture and sand size distribution was measured. pH was measured in water (1:1). Particle-size distribution was measured, after pretreatment with H_2O_2 and sodium hexametaphosphate, using the pipette method on 20-g samples and sand size distribution by sieving the cleaned sand fraction in a column of 16 sieves (AFNOR).

Micromorphology

Undisturbed samples ($12\times12\times8$ cm^3) were oven-dried at 40°C for a week and impregnated with polyester resin that was diluted with styrene monomer (30 % by volume) at room temperature under a low vacuum (5 kPa). A hardener and a fluorescent compound (Uvitex OB, Ciba, Geigy, Hawthorne, NY) were added to the resin mixture in the amount of 1 g.L^{-1}. Resin polymerisation and hardening were complete after about 4 weeks. Thin sections of approximately 30 μm in thickness were prepared based on quartz interference colours. The microscopic observations were made under low magnification using a binocular microscope and at higher magnifications using a bright-field light microscope (Hartmann *et al.*, 1992).

Image analysis

Image analysis was conducted on the thin sections following a systematic approach. Low magnification pictures were taken through the binocular microscope with both incident UV-light directed onto the thin section and transmitted light (Hartmann *et al.*, 1992). A total of 15 pictures were taken of each slide. Images were threshold to discriminate pores (appearing in blue) from the solid area. The obtained bitmaps were analysed using Image-J software. Total pore surfaces, pore size distributions and shape were recorded for each bitmaps. Average values and standard deviation for each slide were derived from the compilation of the previous data.

Results

Bulk density

Dry bulk density profiles of each paired site are presented on Figure 1.

Site 1: Bulk density ranged from 1.38 to 1.52 $Mg.m^{-3}$ in the forest. The 0-15 cm depth is the less dense with 1.38 $Mg.m^{-3}$ but difference was not significant because of the high spatial variability. In the cultivated area, bulk density was significantly higher at all depths except in the 0-15 cm depth interval where variability was high. Highest values were recorded between 20 and 40 cm depth.

Site 2: Bulk density ranged from 1.44 to 1.58 $Mg.m^{-3}$ in the forest with a denser layer between 40 and 60 cm depth. In the cultivated area, bulk density was significantly higher in the first 50 centimetres. No significant differences were observed beneath this depth.

Site 3: Bulk density ranged from 1.42 to 1.50 $Mg.m^{-3}$ under forest with a subsoil (50-100 cm) slightly denser than the topsoil (0-50 cm). In the cultivated area, bulk density was significantly higher in the top 50 centimetres. No significant differences were observed below this depth.

Resistance to penetration

Figure 2 presents gravimetric water content (a) and soil strength profiles (b) for the site 3.

Except in the 0-15 cm depth, soil profile was significantly dryer under forest than under culture. Both forest and cultivation profiles increase with depth ranging from 5 % to 10 and 13 % respectively in the forest and cultivated area. The deepest measure was slightly lower in both cases.

From the surface to 50 cm depth soil strength measures were significantly higher in the cultivated area compare to the adjacent forest. In the forest, strength globally increased with depth from 0.3 to 3.1 kg cm^{-2} at 50 cm. In the adjacent cultivation, soil strength increased rapidly in the 0-20 cm depth interval to reach a maximum of 6.4 kg cm^{-2}. Below this depth, strength decrease to 2.8 kg cm^{-2} at 50 cm depth. At 50 cm depth, there are no significant difference between forest and adjacent cultivation. Below, cultivation soil strength remains constant at about 3 kg cm^{-2} while forest soil had an abrupt increase of strength with very high heterogeneity.

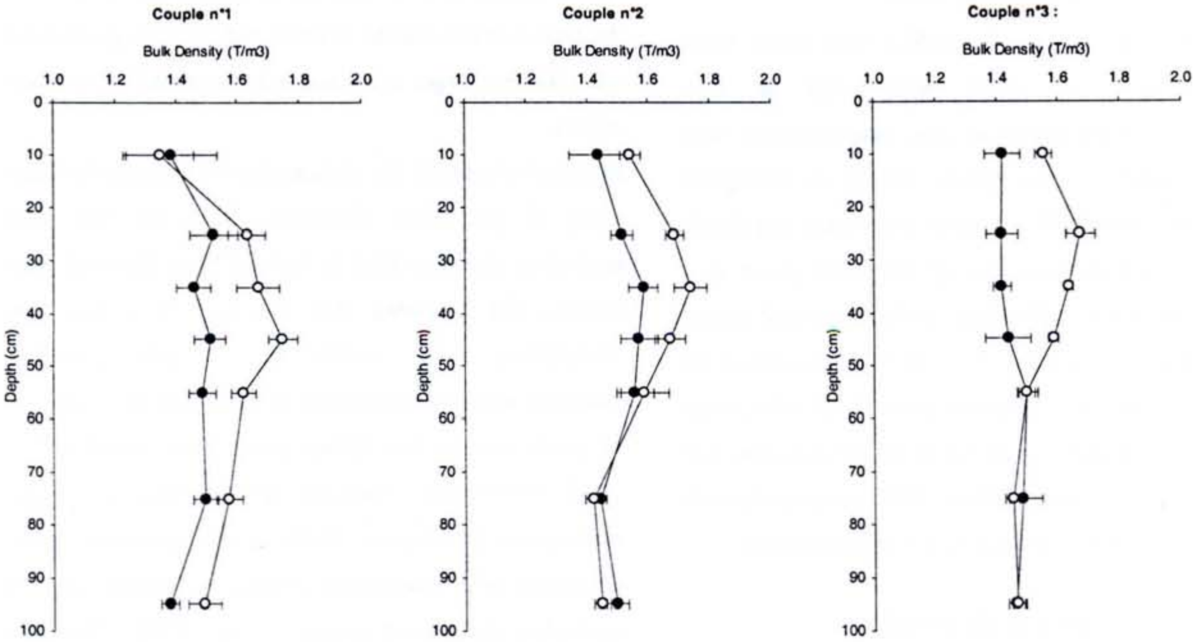

Figure 1: Dry bulk density profiles for the three paired sites. Average for forest (-•-) and adjacent cultivated area (-○-) and associated standard deviation (n=5).

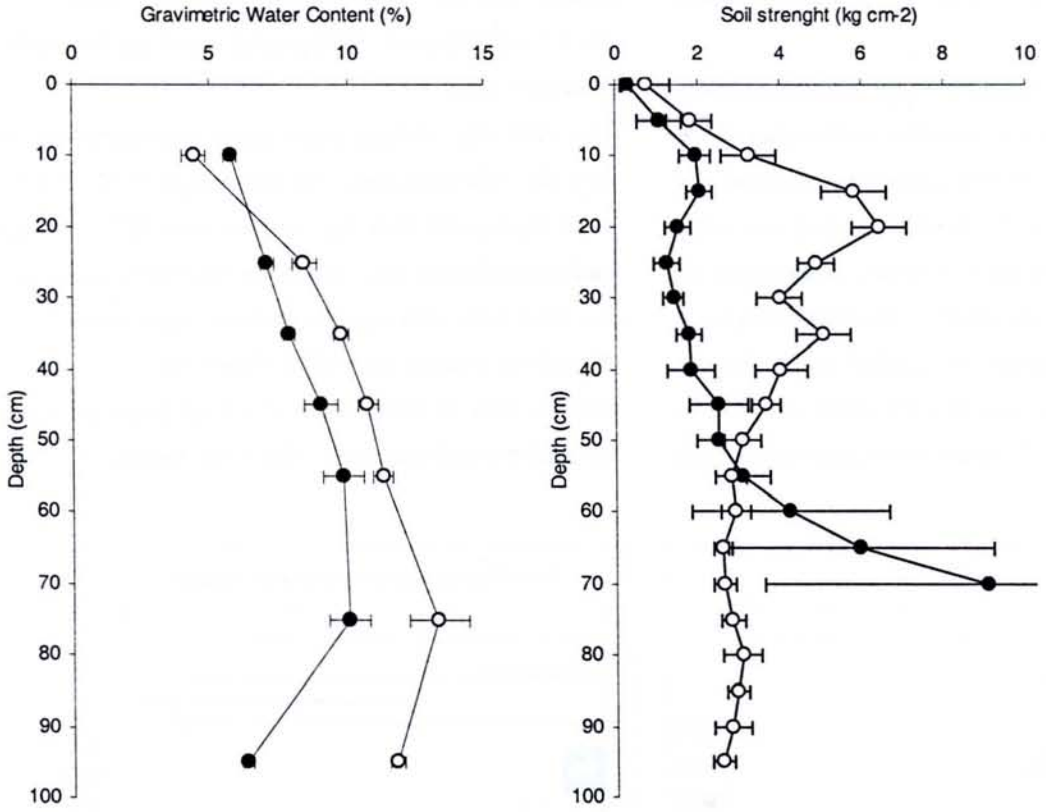

Figure 2: Soil strength measure with pocket penetrometer (b) and associated gravimetric water content profile (a). Average for forest (-•-) and adjacent cultivated area (-○-) and associated standard deviation (n=5).

Qualitative assessment of the porosity

All thin sections of the 3 studied sites have been described under a stereo microscope at low magnification. Independent of site, macroporosity was abundant, connected and mainly related to biological activity under forests. Roots were common at any depth and the general organisation of the solid phase was similar at all depths. However under cultivated areas, very few macropores were observed in the topsoil (5-10 and 25-35 cm samples). Organisation of the solid phase was very tight (especially in the 25-35 cm samples) and biopores quasi inexistent. Below 60-70 cm porosity and solid organisation look similar to the adjacent forest.

Quantitative assessment of the porosity

Considering the similar characteristics described previously, the third site was selected for quantitative investigation of porosity. The study involved image analysis and was confined to the topsoil samples where significant differences were observed between forest and cultivation site.

Quantification of porosity using image analysis involves first the delimitation of pore outlines. At this step of the process, several interconnected pores are considered as a single pore (see Figure 4-a as an example) and solid areas filling the pore are ignored in the calculation of the total area of the pore. This aspect of the calculation has a tendency to over estimate the surface of the largest pores. However, the surface of solid phase included in the pore can be derived from the mean grey value of the considered pore. This latter data has been used to correct the pore surfaces and to estimate the percentage of solid included in a larger pores and not connected to the main matrix.

Figure 3-a presents the distribution of porosity in three class of equivalent diameters. It is of note that equivalent diameter (D_e) is derived from the total pore surface (S_t) assuming that the pore is a disk ($D_e = 2\sqrt{(S_t/2\pi)}$). Pores smaller than 50 µm equivalent diameter were not considered as their area as indication of pixels was to low. Other pores were considered as small (50-170 µm), medium (170-500 µm) and large macropores (> 500 µm). There is no consensus on the definition of a macropore, especially with respect to equivalent diameter (Luxmoore *et al.*, 1990). The limit at 500 µm was decided according to Volkmar (1996) who observed that only macropores of equivalent diameter greater than 500 µm resulted in a positive correlation with root growth. The limit of 170 µm (≈500 pixels) was the middle value between 50 µm (≈50 pixels) and 500 µm (≈5000 pixels) on a logarithm scale of surface area.

The forest site exhibited much larger macropore surface than the cultivated area. The tilled layer (C1) slightly more macropores than the compact layer (C2). For the medium and small macropores, the macropore surface of the tilled layer (C1) was always larger than under forest (F) and the compact layer (C2) (Figure 3-a).

Surface area of solid material filling pores occupied 14 % of the total surface of solid in the forest sample (F)

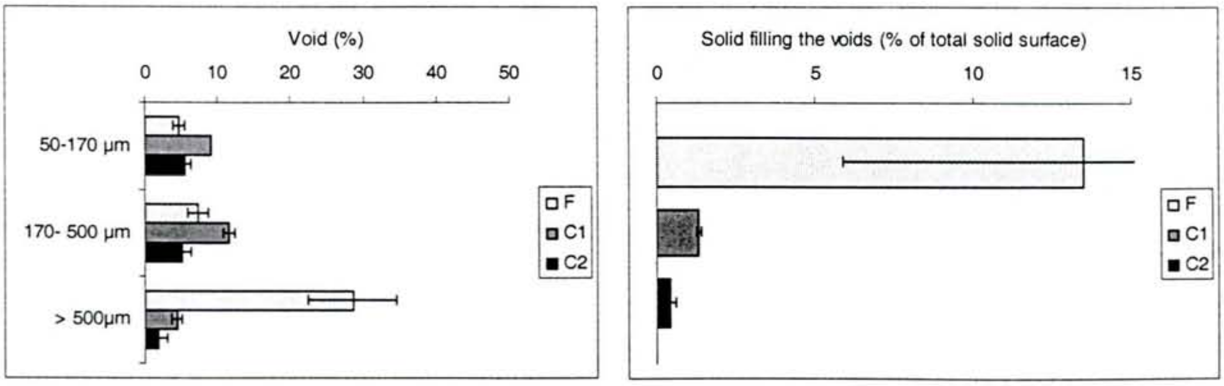

Figure 3: Distribution of the void into three main classes (a) and filling index (b) for the couple 3.

while this was reduced to 1.3 and 0.4 % respectively in the tilled layer (C1) and in the compact layer (C2) of the cultivated area (Figure 3-b).

Figure 4 gives a representative overview of the porosity and of the solid phase organisation under forest (a) and in the tilled layer (b) and in the compact layer (c) of the adjacent cultivated area. These plates illustrate the large porosity and interconnection of pores under forest (a) and the tight organisation under culture (b, c).

Particle size distribution

Sand, silt an clay content profiles for site 3 are presented in Figure 5. While silt content was quite constant with depth (15-18 %), clay content increases with depth both under forest and cultivated site to reach 18 and 20 % respectively in the forest and cultivated site. The cultivated site appeared to have higher clay content than forest down to 1 m depth.

Discussion

Densification and associated resistance to penetration

For the three different sites and the corresponding profiles, this study highlighted that the bulk density in the first 50 cm of the profile was always higher in the cultivated area (Figure 1). This densification was mainly confined to the topsoil except for the first site where density are higher at 1 m. This result confirms the presence of dense layers as described in literature (Hartmann *et al.*, 1999; Imsamut and Boonsompoppan, 1999) and is a consequence of the last 40 years land use and is not a regional specificity of the soil. As a result of this strong increase of soil strength in the first 50 cm, and more especially between 20 and 40 cm, underneath the tilled layer was observed. This high resistance to penetration was not positively correlated to soil moisture as gravimetric water content increased with depth while soil strength increased and then decreased (Figure 2).

The second forest (site 2) presented a beginning of dense layer between 20 and 40, as usually seen in cultivated areas (Figure 1). This could be attributed to anthropogenic perturbations. If the site has been free from mechanised and intensive cultivation, it would be risky to assume that it has never been cultivated. The third site is probably the most didactic example of mechanised agriculture induced compact layer.

Evolution of the porous media

It appears from Figure 3-a that soil compaction affects mainly the largest macropores (equivalent diameter > 500 µm). Because the important fauna activity under forest these pores are assumed to mainly constitute biopores. We concluded that original biopores have been destroyed down to 50 cm depth by mechanical disturbance due to cultivation. Deforestation included the use of heavy material and deep ploughing in order to

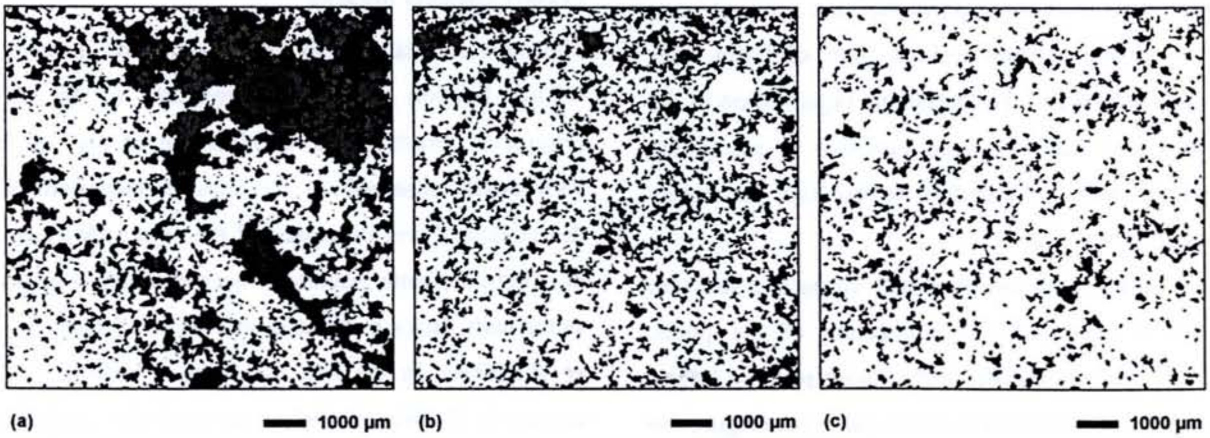

Figure 4: Example of porosity patterns observed respectively in the forest (a), in the tilled layer (b) and in the compact layer (c).

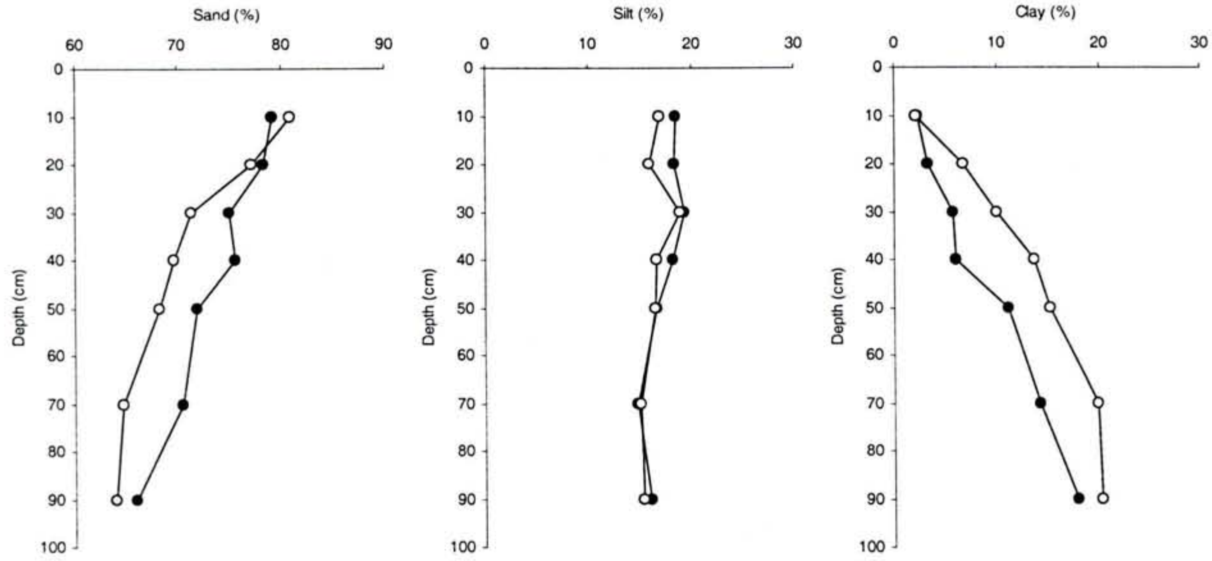

Figure 5: Particle size distribution profile for forest (–•–) and adjacent cultivated area (–○–) of the site n°3.

remove tree roots. This process may change the organisation of the soil to depth through breaking the biopores networks. However successive ploughing and compaction process due to cultivation and the correlative decrease in faunal activity prohibit the development of new biopores, is probably the main cause of the disappearance of soil biopores. While pore size distribution shifted to smaller pores, macropores were less and less affected by the compaction process (Figure 3-b).

It is also interesting to note that the tilled layer contained a greater number of macropores than the compact layer and even than the forest soil for pore <500 µm. This could be attributed to the metastable organisation of the cultivated soil due to tillage practices at ploughing. These macropores are therefore not biopores but mainly inter-aggregate voids.

Another aspect of the reorganisation of the soil structure is the continuity and interconnection of the pores. Porosity is well connected in the forest soil and largest pores are filled with solid material and roots (Figure 3-b ; Figure 4-a). This organisation is not effective in the cultivated soil (Figure 3-b ; Figure 4-b,-c).

In the tilled layer and moreover in the compact layer, the soil matrix is continuous with a large percentage of surfaces in contact between grains or aggregates and then the pores are not connected (Figure 4). This organisation explains the high resistance to penetration measured in such compact layers independent of the moisture content (Figure 2). Because in such an organisation, the grains are unable to move one against the other, penetration of a tool or of a root requires very high energy.

Texture changes induced

The most surprising result is probably the increase in < 2 µm fraction in the cultivated area of the site 3 (Figure 5). Furthermore, the increase of clay content with depth observed in all sites is consistent with description of soil processes of the region (Mitsuchi *et al.*, 1986) and with leaching processes which is consider as the main factor associated with soil evolution (Boivin *et al.*, 2004). In the first two sites, a decline in clay content in the topsoil and an accumulation at depth in the cultivated areas suggested an intensification of leaching under agricultural conditions. No data is presented as the individual clay contents from each of the sites However, in the third site, the increase of clay content affect the whole soil profile. The spatial heterogeneity or lateral redistribution is not exclude but this result also suggests an evolution of constituent under cultivation since it has been observed that < 2 µm fraction contains a significant proportion of small quartz grains (Bruand *et al.*, 2004). Various processes are able to produce fine quartz particles. However in such a context with rather good drainage conditions, desegregation or soil fragmentation seems to be the major phenomenon.

Conclusion

Intensive mechanised agriculture has resulted in a strong densification of sandy soils in Northeast Thailand. This physical degradation is the result of the land use over the 40 last years and affects mainly the 0-50 cm interval depth. Tillage practices decrease temporarily soil compactness, but also delimited a persistent dense layer located between 20 and 40 cm depth. The densification resulted principally in a massive structure with very few macropores and limited biological activity. Absence of biopores and continuity of the solid phase result in a significant increase of resistance to penetration hampering root growth of most of the crops. Land use appeared also as a key factor in soil in textural differentiations of soil horizons. Translocation of clay is probably more intense under cultivation than under the original vegetation. However, the third site presented an increase in clay content at all depth suggesting a fragmentation having an external origin or a in situ production. Since the < 2 µm is known to contain a significant proportion of small quartz grains and that this fraction is of importance in the induration processes, the understanding of the nature and origin of these constituents is necessary to understand and prevent the physical degradation of the soil resource.

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Annexe 4

Compaction processes in a tilled sandy soil

Grégory Lesturgez, Eliane Huard, Daniel Tessier, Christian Hartmann & Roland Poss

Processus de tassement dans un sol sableux labouré

Les sols sableux sont souvent considérés comme inertes sur le plan structural du fait de leur structure massive et de la forte résistance mécanique de leur squelette. Cependant, les sols sableux du Nord-Est Thaïlandais sont sujets à de fortes densifications. Les labours profonds et sous-solages se sont montrés inefficaces pour lutter contre le tassement dans la mesure où l'horizon dense se reforme inéluctablement. L'effondrement structural des horizons travaillés dès les premières fortes pluies et la pression due au passage des machines agricoles sont probablement tous deux responsables de la reformation de la structure massive. Des tests œdomètriques ont été réalisés sur des massifs d'aggregats de manière à caractériser le tassement, l'effondrement et le réarrangement d'un horizon travaillé. L'étude s'est focalisée sur trois horizons, l'horizon labouré actuel, l'horizon compact et l'horizon en dessous. Les résultats ont montré que les trois horizons sont très sensibles à l'effondrement dans la mesure où des affaissements significatifs ont lieu sous de faibles pressions (à partir de 25 kPa) et à de faibles humidités (5-10 %). La fraction argileuse, en faible quantité (5-15 %) joue un rôle fondamental dans les propriétés d'effondrement et l'augmentation de la sensibilité au tassement avec la profondeur s'explique principalement par le taux d'argile. La formation d'un horizon dense à 20-40 cm s'explique par le labour profond du sol qui induit un arrangement métastable d'aggregats, sujet à l'effondrement. Par conséquent, les travaux profonds du sol ne sont pas une alternative pour améliorer sa structure, la formation d'horizons profonds métastables étant à l'origine d'effondrements du sol.

Compaction processes in a tilled sandy soil

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Abstract

Sandy soils are often considered as structurally inert because of their massive structure and the high mechanical resistance of their skeleton. However sandy soils of Northeast Thailand are subject to strong densification. Deep ploughing and subsoiling have not been shown to be effective in overcoming compaction since the compact layer inevitably reforms. Collapse of tilled structure after the first heavy rainfall event and traffic load may be both involved in the restoration of the massive structure. Oedometer tests have been conducted on aggregate beds in order to characterize compaction, hydrocollapse and rearrangement of simulated ploughed layers. The study focussed on three horizons, the actual plough layer, the compact layer and the layer underneath. Results showed that all depths are highly collapsible as significant subsidence occurred under low mechanical pressure (above 25 kPa) and at low water content (5-10 %). The low clay content (5-15 %), appeared to play a key role in collapse properties and increasing sensitivity with depth was mainly explained by the clay content. The formation of a dense layer at 20-40 cm is also explained by the deep ploughing of the soil, creating a metastable arrangement of aggregates sensitive to collapse. Thus, deep tillage is not an option to improve soil structure, as the formation of deep metastable layers is the main cause of soil collapse.

Introduction

Light textured sandy soils widespread in the tropics constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the uplands of Northeast Thailand (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 4 $cmol_c\ kg^{-1}$) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999).

In addition to unfavourable chemical properties, the soil is usually compact from the surface to 40 cm depth, with a maximum in the 20-40 cm layer. This 20-40 cm layer is characterized by a high resistance to penetration (Bruand *et al.*, 2004) that hampers the development of the roots of most crops (Hartmann *et al.*, 1999). Deep ploughing and subsoiling have been disappointing as the compact layer reforms rapidly.

Soil compaction in agricultural systems is a worldwide concern that has received considerable attention over the past decades (Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005). Soil compaction is defined as: "the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density" (Soil Science Society of America, 1996). The vast majority of soil compaction in modern agriculture is often attributed to traffic load (Flowers and Lal, 1998), however other processes can be involved in soil compaction. The formation of a dense subsoil layer known as "fragipan" is interpreted by soil collapse under its own weight (Assallay et al., 1998). This process occurs when a metastable arrangement of particles is wetted under a constant confining pressure (weight of the top layer in the case of natural collapse) (Assallay et al., 1997).

Dry compaction, hydrocollapse (also known as hydroconsolidation) and traffic load can be involved in the formation or the reformation of a compact layer. The objective of the study was to investigate the processes of soil compaction in a tilled sandy soil subjected to non-flooding rains and evaluate their respective contribution to total soil compaction. Experiments focussed on uniaxial compactability, hydrocollapse and rearrangement under traffic load.

Material and methods

Soil characteristics and sampling

The samples were collected in a sugarcane field located in Ban Phai district, 40-km from Khon Kaen City, Northeast Thailand (16° 08' N, 102° 44' E). The choice of the site was based on a previous investigation that highlighted the presence of a compact layer located at 20-40 cm depth that was representative of the general situation of subsoil compaction. The characteristics of such a compact layer were described on a similar soil in the same region by Bruand *et al.* (2004).

The soil has a sandy texture with massive structure. It belongs to the Nam Phong soil series (Imsamut and Boonsompoppan, 1999) and was classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) or Arenic Acrisol (FAO classification).

Three undisturbed samples were collected from the vertical face of a pit, respectively in the topsoil (0-15 cm), in the compact subsoil (15-25 cm) and underneath the compact layer (40-50 cm). Selected chemical and physical characteristics of the samples are presented in Table 1. Mineralogical characteristics of the

Table 1: Selected soil physical and chemical properties of the Arenic Acrisol at the study site.

	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in μm*							pH	CEC ($cmol_c\ kg^{-1}$)	BD ($Mg\ m^{-3}$)	
	<2	2-20	20-50	50-200	200-500	500-1000	1000-2000			Mean	SD
10-15 cm	70	81	122	614	100	11	2	6.1	3.2	1.61	0.13
25-35 cm	86	87	122	601	94	9	2	5.6	3.0	1.75	0,04
40-50 cm	136	88	115	565	86	9	2	4.6	3.9	1.67	0.02

CEC is cation-exchange capacity measured in cobalty-hexamine, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n=5).

studied soil were investigated using X-ray diffraction. When the sand and silt fractions were exclusively constituted of quartz, the clay fraction included kaolinite, traces of illite and a significant proportion of small quartz particles.

The three samples were identical in their mineralogy and the particle size distribution of the sand fraction. They differed only in their clay content (from 70 g kg^{-1} in the topsoil to 136 g kg^{-1} in the deepest layer). A control sample (pure sand material) was prepared from the topsoil horizon by sieving at 50 µm the material after dispersion in sodium hexametaphosphate.

Sample preparation

The samples were manually crumbled in the lab in order to produce small aggregates similar to tillage-induced aggregates. The aggregates were poured into a ring 50 mm in diameter, and 18 mm in height laid on a ceramic plate using a small funnel fixed 5-cm above the middle of the ring. The ring was overfilled, then the surface was carefully levelled off, and the assemblage thoroughly cleaned with a small brush. The assemblage was then installed in the oedometer and the top cap gently positioned. Preliminary tests had shown that the preparation of the aggregate beds using this method allowed the formation of a metastable arrangement of aggregates with a bulk density similar to that of the topsoil after ploughing.

Design of the oedometer apparatus

The oedometer test is classically used for consolidation and compression studies of fine-grained soil samples, such as clays and silts, since it recreates the conditions of volume change with zero lateral strain (i.e. one-dimensional compression). The oedometer apparatus used (Figure 1) allows the application of an axial load that ranges from 0 to 1500 kPa. We applied a range of 29 pressure steps (2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1300 and 1500 kPa), with 5 minutes interval between each step (minimum duration to reach equilibrium). The change in volume of the samples was recorded continuously by measuring the vertical displacement of the rigid top platen used to apply the load. The design of the apparatus allows the injection of water on the top of the sample. Drainage was free through the porous plate located below the sample. The volume of water injected into and drained from the samples could also be recorded. Bulk density and average water content were derived from these measurements. The background noise of the oedometer originating from internal deformation (porous plates) and elasticity of the membrane was estimated during preliminary tests on uncompressible Plexiglas cylinders and results were corrected accordingly.

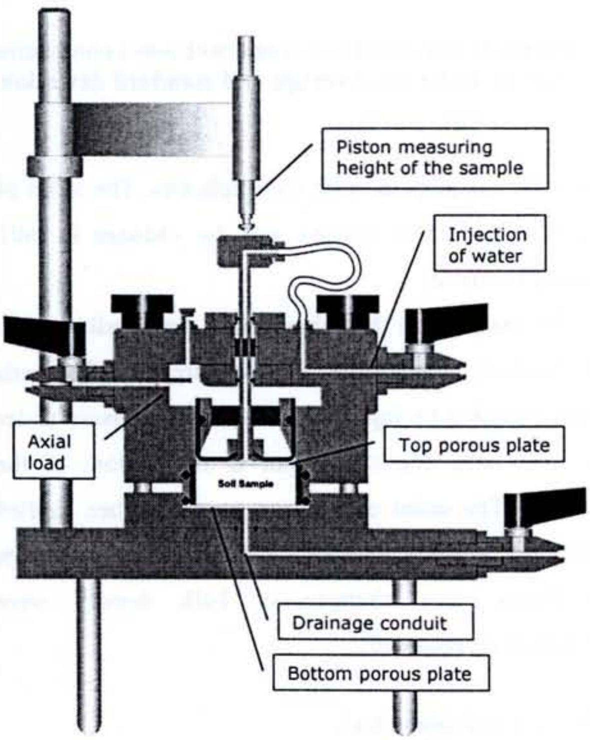

Figure 1: Oedometer apparatus

Dry and wet compaction curves

We used the following experiment to characterize the compaction in dry and wet conditions:

(a) To characterize the behaviour in dry conditions, an air-dried aggregate bed of the control and the three

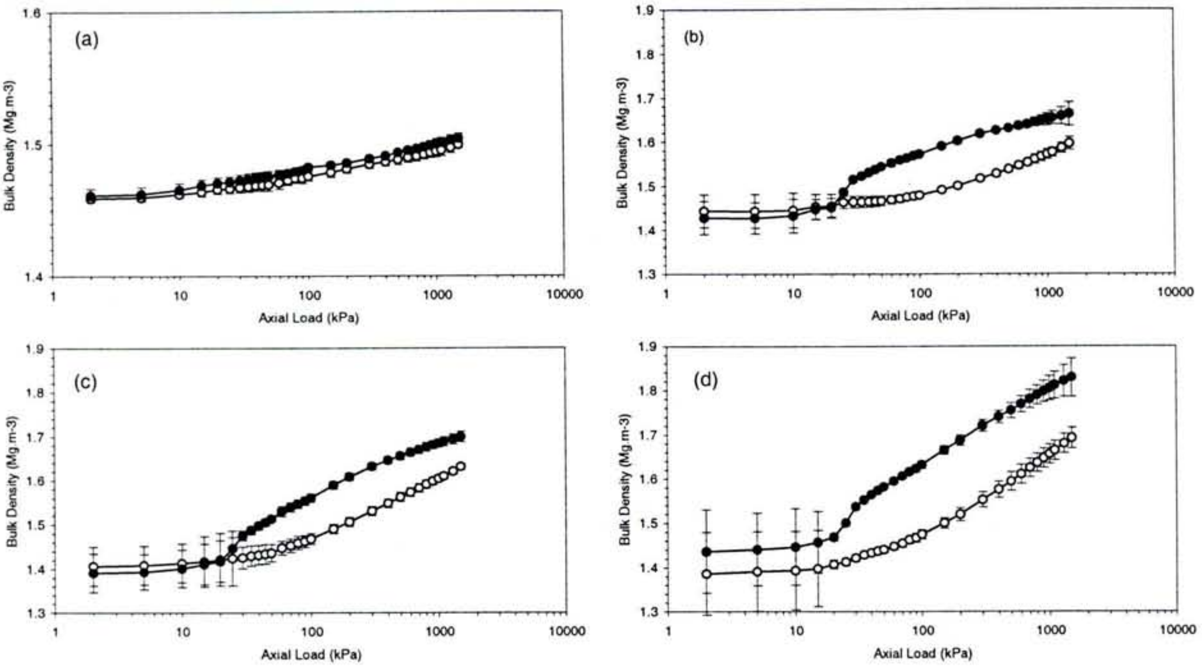

Figure 2: Air-dried (–○–) and wet (–●–) compaction curves for (a) sand fraction, (b) 0-15 cm, (c) 25-35 cm, and (d) 40-50 cm. Average and standard deviation (n=5).

horizons was prepared with five replicates. The series of pressure steps was applied and the changes in bulk density recorded.

(b) To characterize the behaviour in wet conditions, an identical set of aggregate beds was prepared. The beds were saturated by injecting water at no pressure under no load until drainage began at the bottom of the samples. The series of pressure steps was then applied while that samples were kept saturated in free drainage conditions. The changes in bulk density were continuously recorded.

Hydroconsolidation tests

Hydroconsolidation is characterised by an abrupt change in bulk density of samples loaded at their *in situ* water content and then flooded. Hydroconsolidation under a constant load P_w was studied in a three-stage test:

(a) Air-dried samples (5 repetitions for each depth) were loaded step by step to a constant load P_w of 2, 100, 500 and 1500 kPa.

(b) While the axial load P_w was maintained on the sample, water was injected at 50 mm^3 min^{-1} through the porous plate located on the top of the sample until drainage started at the bottom of the porous plate.

(c) The load was then increased step by step on the wet samples from P_w to 1500 kPa. Water continued to be added freely at no pressure to keep the sample wet until the end of the test.

This test was similar to that described by Assallay et *al.* (1998) except that we did not saturate the sample at P_w with a single addition of water but injected the water at a constant rate to determine the collapse as a function of water content.

Rearrangement tests

The purpose of this test was to characterise subsequent compaction (i.e. rearrangement processes) under a series of identical axial loads in wet conditions. The test consisted of a series of pressions/relaxations applied on wet samples:

(a) Five samples of each horizon were saturated and then loaded step by step to create stresses P_R of 100, 500 and 1500 kPa. Water was added freely at no pressure to keep the samples wet throughout the test.

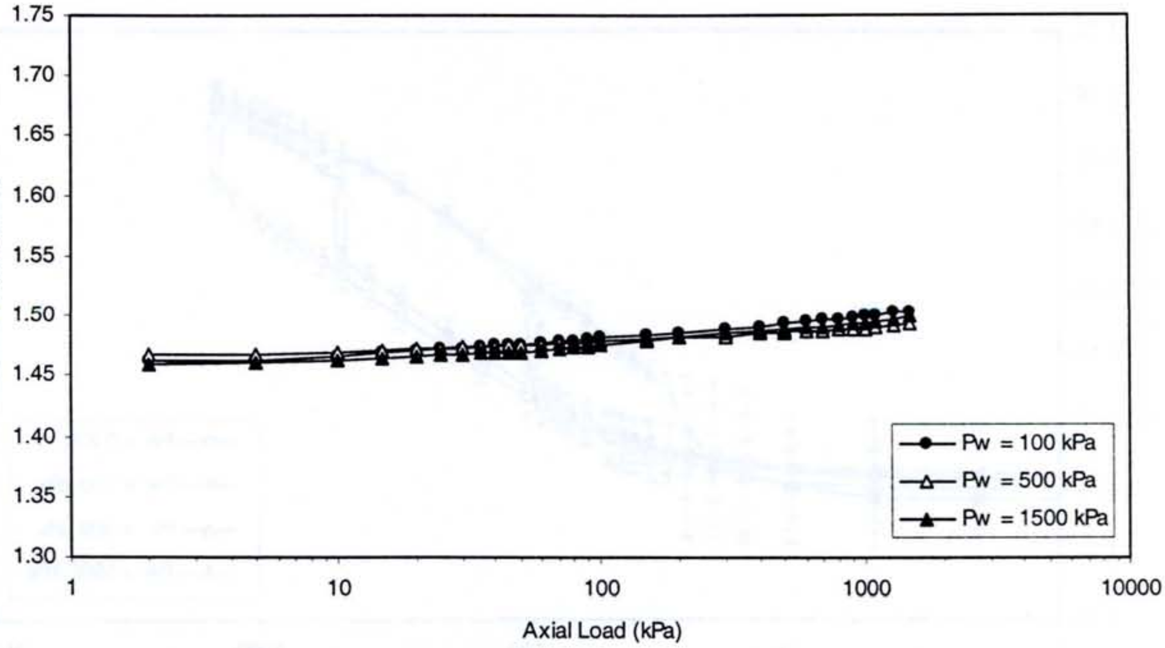

Figure 3: Hydrocollapse curves for pure sand material.

(b) A series of 70 cycles of pression (P_R) and relaxation (0 kPa) was applied on the wet samples. Bulk density was continuously recorded.

Results

Figure 2 presents the compaction curves using the classical compaction approach. Both dry and wet bulk density measurements are presented as a function of axial load. For the control (pure sand) compaction due to axial load was very low over the range of pressures and there was no significant difference between dry and wet curve (Figure 2-a). Compaction was low and highly heterogeneous between replicates for the three soil samples up to 25 kPa (Figure 2-b, c, d). There was no significant difference between the dry and wet samples. Bulk density increased sharply above 25 kPa and became more homogeneous. The consolidation pressure was around 100 kPa for all soil samples (Figure 2-b, c, d). Beyond this limit, the bulk density increased with depth for any given load. At 1500 kPa the dry bulk densities reached 1.60, 1.63 and 1.69 Mg.m^{-3} for the 0-15, 15-25 and 40-50 cm depths, respectively.

Figure 3 presents the results of the hydroconsolidation test on the pure sand material. The compaction either in dry or wet condition was almost insignificant and there was no significant difference between the dry curve and the wet curve at any pressure. Therefore, the collapse was insignificant. Figure 4 presents the results of the hydroconsolidation test together with the results of the compaction test for the 25-35 cm depth layer. Collapse resulting from water injection (represented on the chart as white arrows), always resulted in a final bulk density between the dry and the wet compaction values. The increase in bulk density as a result of hydrocollapse was quite similar over the range $50<Pw<1500$ kPa, even though the largest bulk density change was recorded for an axial load of 100 kPa. The bulk density after hydrocollapse was sometimes significantly lower than that of the wet curve ($P<0.05$). However, the differences was no more significant when the loads were increased

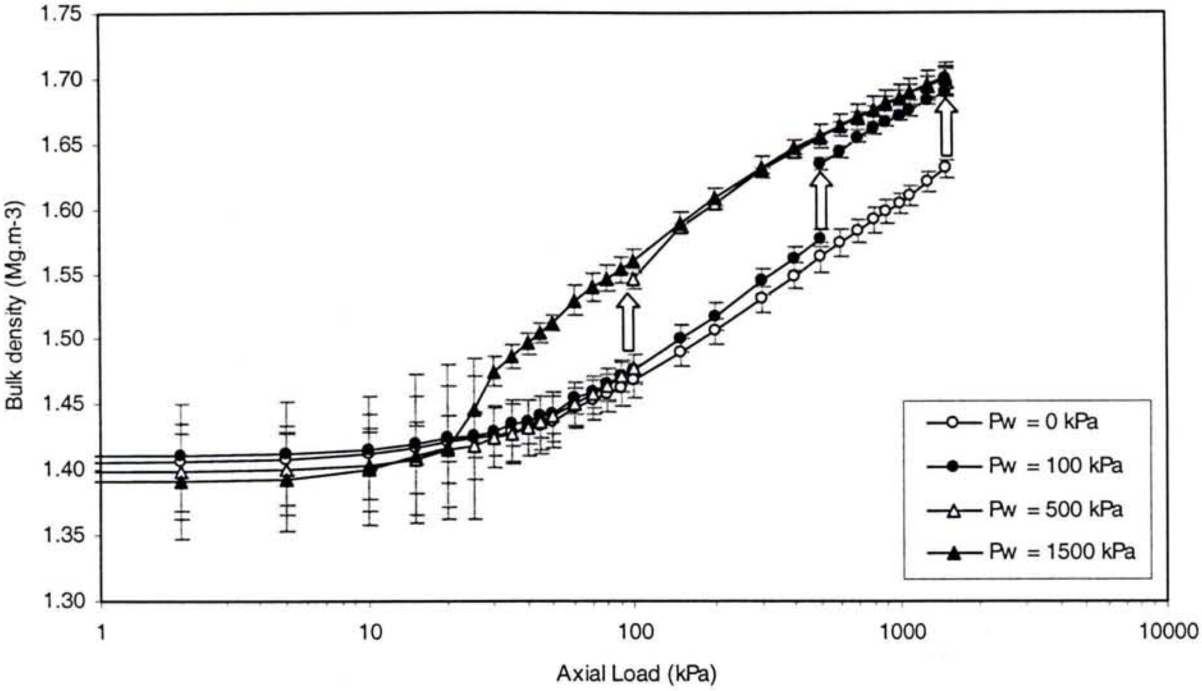

Figure 4: Hydrocollapse curves for 25-35 cm depth soil sample.

after hydrocollapse had occurred. As the dry and wet compaction curves tend to get closer at high pressure, we can assume that for very high loads, no more collapse will occur.

Figure 5 presents the changes in bulk density with increasing water content at constant load ($P_w = 1500$ kPa) for the three soil horizons. Two replicates are presented for each depth as a mean to highlight heterogeneity. In agreement with the compaction in wet conditions, the lowest collapse was recorded for the 0-15 cm depth sample, and the intensity of collapse increased with depth. Collapse always occurred in a range of gravimetric soil moisture between 5 and 15 %. The volume of water to inject to complete the process increased with depth.

Figure 6 presents the rearrangement curves. The bulk density increased by at least 0.1 $T.m^{-3}$ at $P_R = 1500$ kPa from the initial compaction to the end of rearrangement cycles. The soil samples presented significant elasticity. The material recovered a significant proportion of the porosity when the axial pressure is relaxed but some of the deformation is non-reversible and the bulk density increased for each cycle. The deformation intensity decrease as number of cycles increase. The rearrangement intensity increased with depth. Similar results were obtain at $P_R = 100$ and 500 kPa (data not shown). The intensity of rearrangement was function of the applied pressure.

Discussion

Compaction of the pure sand

For the pure sand, the sensitivity to compaction, in dry and in wet conditions as well, was very low and independent of the applied pressure (Figure 4). The sand grains did not reorganize under pressure, even when wet. This result suggests that the lubricant effect of the water was ineffective in the case of this material. Two factors can explain this unusual behaviour. Firstly, the bulk density was already 1.46 $T\ m^{-3}$ under the very low

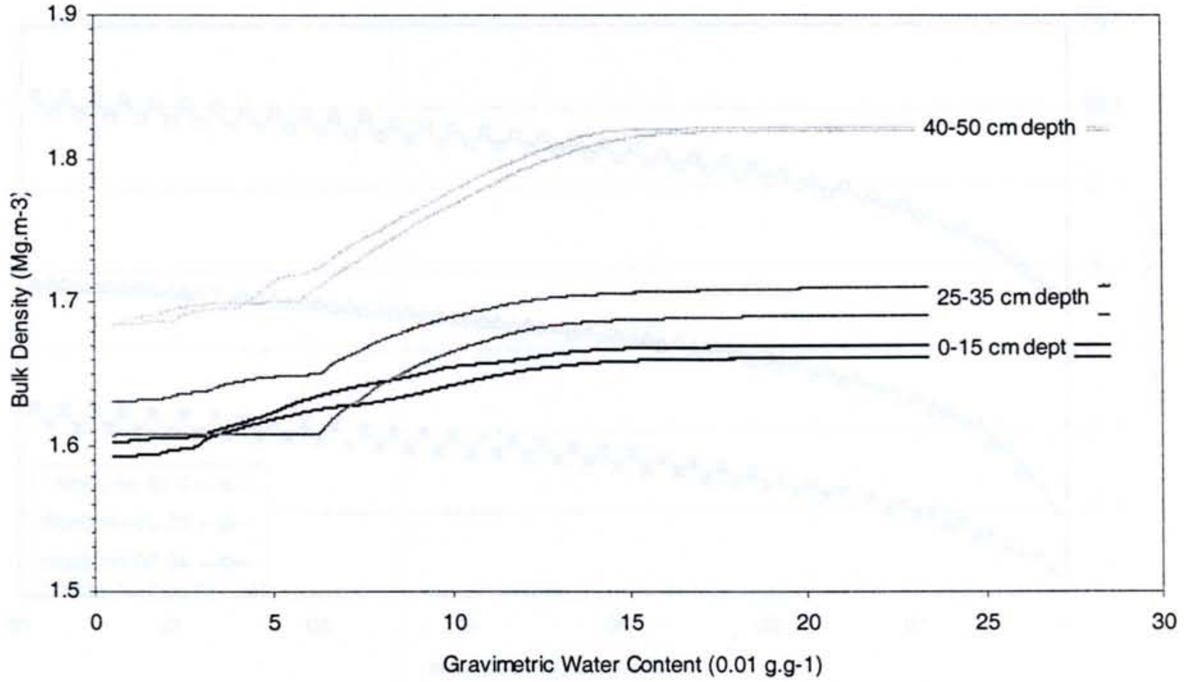

Figure 5: Bulk density versus depth during collapse at Pw = 1500 kPa.

pressure applied at the beginning of the experiment, probably because the size of the sand grains was distributed over a large range (Table 1). Secondly, most sand grains had a jagged shape (Bruand *et al.*, 2004) that probably resulted in interlocking between the grains.

Compaction of soil samples

In contrast, the compaction curves of the soil samples in wet condition proved that the same sandy material with a small amount of clay particles was highly compactable. In dry conditions compaction started at around 25 kPa and increased with increasing pressure until 1500 kPa. In the case of aggregate beds, collapse was in part the consequence of the deformation of the aggregates (Faure, 1976). This process was not active in the pure sandy material under study because no aggregates developed. Dry compaction may in part result from the deformation of clay particles. However, the contribution of this process must be limited, given the low clay content of the material (Table 1) and the high proportion of quartz grains within the clay fraction (Bruand *et al.*, 2004). The major contributing factor associated with compaction was probably due to lubrication in dry conditions, the planar-shaped clay minerals helping the sand grains slip against each other.

Hydrocollapse

In wet conditions hydrocollapse proved to be a phenomenon that developed fully under constant pressure at any given pressure (Figure 3). Indeed, whatever the initial pressure, the final bulk density was almost identical to the bulk density obtained by compaction in wet conditions. This result, consistent with the observations of Assallay *et al.* (1998) on loess materials, has a direct application in predicting the collapse. Maximum collapse under any load (traffic load or weight of the soil profile) can indeed be estimated by the difference between the dry and wet compaction curves under the considered load. Maximum hydrocollapse was recorded for $P_w = 200$ kPa, close to the value of 100 kPa observed by Assouline *et al.* (1997) on aggregate beds. It has been shown in aeolian deposits that collapse needed a small amount of clay to develop (Rogers *et al.*, 1994), and that collapse intensity

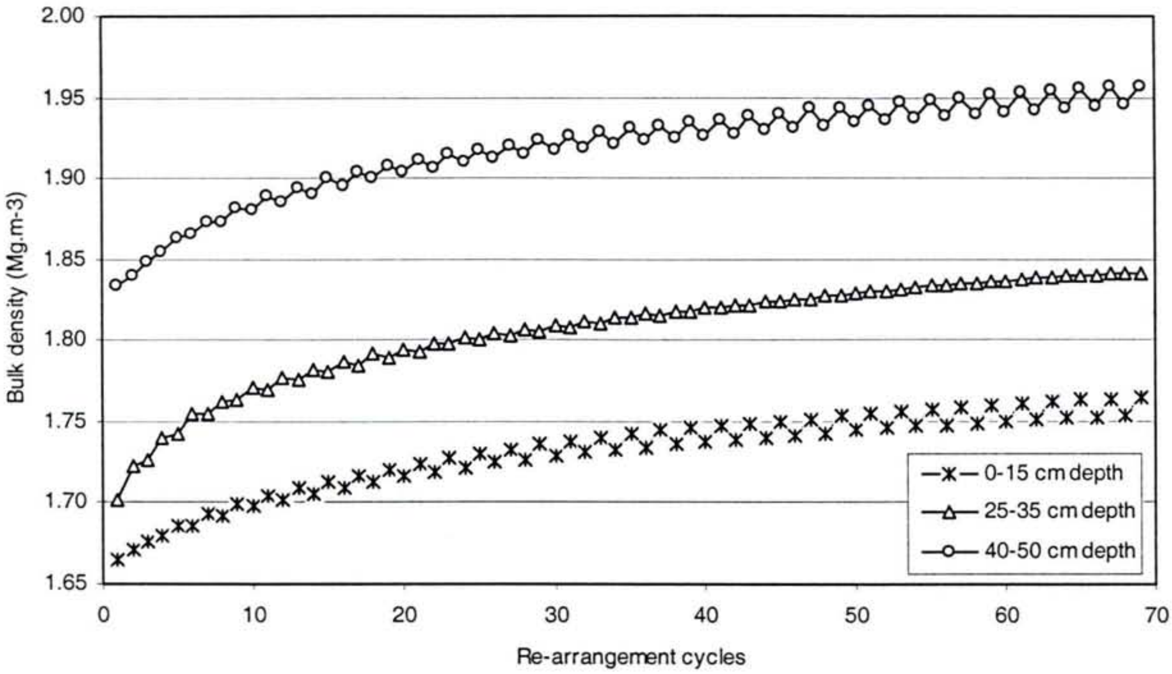

Figure 6: Bulk density during re-arrangement cycles (0-1500 kPa).

increased with clay content up to 25 % clay (Assallay *et al.*, 1998). The same increase in hydrocollapse with clay content was observed in this experiment, but the range of clay content covered by the three samples was not sufficient to determine a maximum value. The increase in water content with clay content for hydrocollapse to develop (Figure 5) suggests that the process is related to the hydration of the clay minerals. Faure (1976) mentioned the importance of the clay fraction in compaction of sandy soil and introduced the notion of water potential and clay hydration. In the three horizons hydrocollapse started between 3 and 7 % of gravimetric water content. This low water content proves that the phenomenon becomes active in any horizon as soon as it gets wet. The samples presented a mechanical behaviour similar to metastable deposits (Assallay et al., 1997). These properties, usually associated with loess and loess-like deposits (Jefferson et al., 2003), are therefore not confined to silty aeolian materials and develop also in sandy soils.

Rearrangement in wet condition

The mathematical description of soil compaction is based on relationships between bulk density and applied stress (Assouline, 2002). This approach assumes that after a sample has been consolidated under a pressure P_1, the consolidation would resume only for a pressure $P_2>P_1$ (Guérif, 1982). This theory is not applicable to the results of this study as a series of successive stresses under the same axial load resulted in a substantial increase in bulk density (Figure 6). The relaxation between successive stresses allowed the internal friction between sand grains to decrease and therefore permitted the network of forces to reorganise during the next axial load, leading to increased bulk density. The asymptotic shape of the curve showed the development of the soil structure towards the highest possible bulk density. The rearrangement test in wet condition is probably the most representative test to simulate vehicle traffic load as it models as series of confined uniaxial stresses under the same pressure.

Contribution of the different processes to total soil compaction

The contribution of dry compaction, hydrocollapse and rearrangement to bulk density increase was estimated from our results at a load of 1500 kPa. (Figure 7). The effect of the three processes on bulk density increased with clay content. However, the contribution of the three processes to bulk density increase remained similar in relative value whatever the clay content. Dry compaction represented around 50 % of total compaction, when hydrocollapse and rearrangement ranged between 20 and 30 %. In the field dry compaction and hydrocollapse under low pressure (weight of the upper soil horizons) are the first two processes to develop after tillage. The many tillage operations usual in the region induce then a succession of traffic loads that rearranges the fabric to produce the usual massive structure with high bulk density. The close lay out of grains, with small particles filling the voids left between bigger ones, has been described by Bruand *et al.* (2004) as the main factor of high resistance to penetration of the compact layer. Finally, as soil sensitivity to compaction increases with clay content and clay content increases with depth, the most sensitive horizons are the deepest. As a consequence the deeper the soil tillage, the higher the risk of compaction and the final density. The bulk density is highest in the 20-40 cm layer probably because this layer supports the wheels of the tractors during ploughing (at least three times a year). Surface axial load due to vehicle traffic may also be transmitted to subsoil horizons through the massive and often dry topsoil, increasing bulk density through rearrangement processes. In the field the highest bulk density values were recorded in the 20-40 cm depth interval despite the higher sensitivity to compaction of the lower horizon. Two kinds of tillage operations are to distinguish: frequent tillage of the 0-20 cm interval depth and some punctual deep tillage operations with the objective to break the compact layer. As the soil is highly collapsible and sensitive to re-arrangement, the density of the post-tilled layer reach inevitably high values as a function of time. The frequency of tillage in the topsoil (0-20 cm) do not allow high density as in the 20-40 cm interval depth as the structure return frequently to the tilled state. However, the 20-40 cm interval depth beneficiate of enough time to accumulate combine effect of the traffic load. As for the lower layers (> 40 cm depth), tillage operation have never change organisation of the structure and if aggregates beds from this layer are highly sensitive, the actual massive structure is stable. Actually, it has been shown that tilled layer are much more sensitive to compaction than massively structured or already compacted subsoil (Schäfer-Landefeld *et al.*, 2004). Porosity of this layer is mainly constituted of biopores which are usually stable

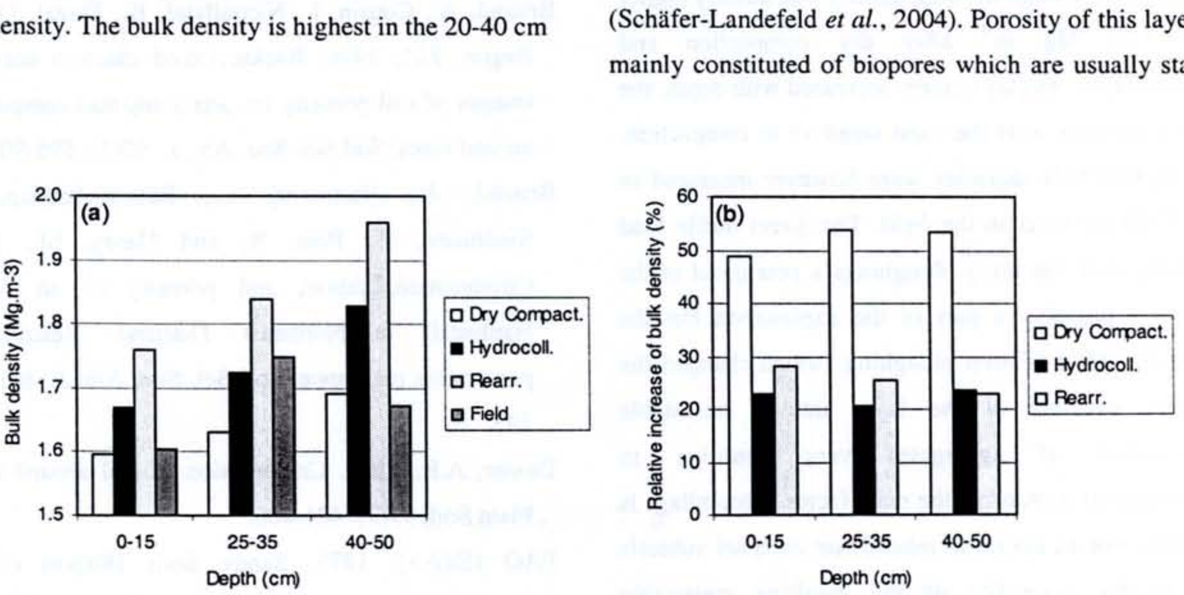

Figure 7: Dry compaction, hydroconsolidation and rearrangement for each depth at $P_w = 1500$ kPa.

because they develop in a stable structure (Dexter, 1987; Bruand *et al.*, 1996). These results suggest that deeper the soil is tilled and higher is the risk in obtaining high bulk densities.

Conclusion

Without clay, the compaction of the sandy material studied under uniaxial load was trivial, even in wet conditions. The same material was highly sensitive to compaction with a clay content of 70 g kg^{-1}, and the sensitivity to compaction increased with increasing clay content. Compaction in dry condition, hydrocollapse (collapse under increasing water content at constant pressure) and rearrangement under a series of successive loads were more pronounced when clay content increased. However, the contribution of each phenomenon to final bulk density was approximately constant whatever the clay content. Most part of soil compaction (around 50%) was due to dry compaction. Hydrocollapse explained about half of the remaining compaction. Hydrocollapse was responsible for sharp increases in bulk density as a result of small increases in water content (gravimetric water content between 3 and 7 %), even under low pressure. The rearrangement under successive loads explained 20 to 30 % of the final bulk density, even though the bulk density was already higher than 1.65 Mg m^{-3} after dry compaction and hydrocollapse. As clay content increased with depth, the deeper horizons were the most sensitive to compaction. The highest bulk densities were however measured in the 20-40 cm layer in the field. The direct traffic load resulting from the many ploughings a year usual in the region is probably a part of the explanation but the structural effect of deep ploughing (which changed the massive structure of the layer into a metastable organisation of aggregates very sensitive to densification) is probably the main factor. Deep tillage is therefore not an option to rehabilitate compact subsoils due to the instability of the resulting metastable structure.

Acknowledgments

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Annexe 5

Silica precipitation as a result of tillage in a sandy soil?

Grégory Lesturgez, André Prone, Roland Poss, Daniel Tessier & Olivier Grünberger

Précipitation de silice induite par le travail du sol ?

Les sols sableux du Nord-Est Thaïlandais présentent un horizon très résistant à la pénétration des racines. Cette résistance varie beaucoup malgré de faibles variations de densité apparente. L'arrangement serré des constituants a été considéré comme l'un des principaux facteurs expliquant les fortes résistances à la pénétration des sols. Cependant, dans la mesure où des phénomènes de précipitation de silice amorphe ont été observées dans certains sols de la région, la cimentation par la silice pourrait également intervenir. Une analyse de la microtexture des quartz (exoscopie) au microscope électronique à balayage (MEB) a été conduite sur un profile de sol présentant de fortes résistances à la pénétration. Les échantillons de sol ont été comparés en fonction de la profondeur et comparés au matériau parental. En plus des caractères hérités du matériau parental, les grains de quartz présentent une combinaison de figures de dissolution et précipitation. La dissolution se manifeste par des creusements, figures de dissolution géométriques et anastomosées. La précipitation se manifeste quant à elle par des globules siliceux, des fleurs de silice, de la néogènese de quartz et des surfaces de contact. La comparaison sol-matériau parental suggère que la précipitation et la dissolution sont d'origines pédogénétiques. La différenciation de ces phénomènes en fonction de la profondeur suggère que ces phénomènes sont toujours actifs et probablement influencés par les modifications agricoles du profil de sol. La précipitation qui a désormais préférentiellement lieu dans l'horizon compact serait le résultat des évolutions structurales et hydrodynamiques induites par le travail du sol. Des propriétés de surfaces comme la cimentation de particules et les surfaces de contact peuvent en effet augmenter les points de contact et les frictions entre les particules solides, la conséquence étant une augmentation de la résistance du sol.

Silica precipitation as a result of tillage in a sandy soil?

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Abstract

Sandy uplands of northeast Thailand have subsoil with high resistance to root penetration that varies even through there is few variations in bulk density. Close packing of sand particles has been considered as one the main factors explaining high resistance to penetration of the soil. However, since amorphous silica precipitation has been observed in some soils of the region, cementation may also be part of the explanation. A quartz microtexture analysis, based on SEM observation of the quartz grains, has been conducted on a soil profile with high resistance to penetration and samples have been compared to parent material. Beyond mechanically induced features inherited from the parent material, quartz grains of the soil showed a combination of chemical dissolution and precipitation features. Characteristics of dissolution include etch patterning, triangular shaped etch pits and solution features. Precipitation forms include globules, silica flower, neogenesis and preserved grain contact faces. The comparison between soil profile and original material suggested that precipitation and dissolution was mainly post deposit. Differentiations of these features as a function of depth suggested that silica dynamics are still active and probably influenced by agricultural modifications of the soil profile. Preferential precipitation in the compact layer is assumed to be the result of structure and hydrodynamic changes induced by tillage. Microtexture features as adhering particles and contact surface may resulted as an increase of particle contacts and frictions, and therefore can explain high soil strength.

Introduction

Light textured sandy soils are widespread in the tropics and are of economic importance for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the Northeast Thailand uplands (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 2 cmol$_c$ kg^{-1}) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999).

In addition to unfavourable physico-chemical properties, the formation and persistence of a compact layer at 20-40 cm depth is common in cultivated area. This dense layer is characterized by high resistance to penetration (Bruand *et al.*, 2004) and hamper rooting of most of the crops (Hartmann *et al.*, 1999).

High resistance of soil to penetration is usually well correlated to various factors including moisture, bulk density, shape of the grain, microtextures of the grain and possible cementation. In this respect, Bruand *et al.* (2004) highlighted that close arrangement of grain are involved in the high resistance to penetration observed even in wet conditions. SEM observations revealed, in some soils of the region, the occurrence of amorphous silica precipitation. Precipitation of silica as amorphous gel is able to increase significantly the cohesion of a sandy material.

In order to investigate this topic, a complete quartz grain microtextures study has been conducted on a soil profile of the region presenting a layer with high resistance to penetration. Quartz microtextures features related to silica dynamic have been described and their occurrence quantified. Soil samples were studied from various depths and compared to a preserved original material in order to differentiate features related to the parent material from features induced by pedogenetic process and land use.

Materials and methods

Study site and sampling

Northeast Thailand is characterised by a semi-arid tropical climate with a distinct rainy season from April to October and a dry season from November to March. The average annual rainfall is 1020 mm. Annual and monthly rainfall is highly variable on a year to year basis (min.=599 mm and max.=1446 mm for the period 1971-1998). Rainfall generally exceeds evaporation during the growing season and there are at least 3 months of dry season in the year.

Soil samples were collected in a sugar cane field located in Ban Phai district, 40-km from Khon Kaen City, Northeast Thailand (16° 08' N, 102° 44' E). The choice of the site was based on previous investigation that highlighted the presence of a compact layer located at 20-40 cm depth and representative of the regional problem of soil compaction. Samples were also collected in a preserved outcrop considered as representative of original material.

The soil at the site is of a sandy texture with massive structure and belongs to the Nam Phong soil series (Imsamut and Boonsompoppan, 1999). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) and Arenic Acrisol (FAO

Table 1: Selected soil physical and chemical properties of the Arenic Acrisol at the study site.

	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in μm*							pH	CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1000	1000-2000			Mean	SD
10-15 cm	70	81	122	614	100	11	2	6.1	3.2	1.61	0.13
25-35 cm	86	87	122	601	94	9	2	5.6	3.0	1.75	0.04
40-50 cm	136	88	115	565	86	9	2	4.6	3.9	1.67	0.02

CEC is cation-exchange capacity measured in cobaltyhexamine, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n=5).

classification).

Selected chemical and physical characteristics of the soil and original material are presented in Table 1. Mineralogical characteristics of the studied soil were investigated using X-ray diffraction. Sand and silt were exclusively constituted of quartz, clay fraction included kaolinite, trace of illite and a significant proportion of small quartz particles.

Samples were collected, on the vertical face of a pit, respectively in the plough layer (0-15 cm), in the compact layer (15-25 cm) and underneath the compact layer (40-50 cm).

Sand size distribution

After homogenisation of the soil sample, 150-g sub-sample was collected using a mass separator in order to preserve the particle distribution through sub-sampling. The sand fraction (>50 µm) was extracted by sieving after dispersion of the soil in a sodium hexametaphosphate solution. The particle size distribution of the sand fraction was determined on the entire sub-sample using a vibrating column of 16 sieves (AFNOR).

Morphoscopy

The morphoscopic analysis describes the sand grains using a low-power stereo microscope. The grains were split into four size fractions to avoid overlapping: coarse sand (2–0.5 mm), medium-sized sand (0.5–0.2 mm), fine sand (0.2–0.1 mm) and very fine sand (0.1–0.05 mm). Five samples of 400 grains were collected from each fraction. The grains were spread on a 24x36-mm piece of black graph paper and abundance of the four environmental morphoscopic classes (Prone, 2003) were quantified using a low-power stereo microscope, i.e. Round frosted (RF), Blunt Shinny (BS), Unworn Evolved (UE), and Unworn (U).

Quartz grains microtextures

The exoscopy analysis was conducted on quartz grains of each size fraction and each morphoscopic class using a scanning electron microscope (SEM). A total of 100 grains were observed for each size fraction (25 grains for each environmental parameter). The 25 grains were lined up on a brass block covered with double-sided tape, covered with gold, and then observed using a scanning electron microscope (SEM). In order to process a semi-quantitative analysis of the samples, a grid of description containing a total of 232 features and based on the grid proposed by Prone (2003) was filled up. Quartz grain microtextures were observed on all grain according to Krinsley and Doornkamp (1973), Le Ribault (1977; 1978) and Prone (2003). It is a note that the relative proportions of feature on a single grain were not taken into account in our semi-quantitative method. Observations were done at various magnifications on each grain and the presence or absence of a feature was noticed in the grid. Then, percentages of grain affected by each feature were derived from the table. For readability, only main observed features are presented in the tables and pictures are selected illustration of the observed microtextures.

Results

Sand size distribution and morphoscopy

Figure 1 presents the sand size distribution of the three soil horizons and of the parental material. No significant difference were observed, nor between soil horizons, nor between soil and parental material (χ^2 tests). From morphoscopy, samples are mainly composed of fine sands with a mode between 125 and 160 µm.

Figure 2 presents the morphoscopic characteristics of the sand grains (soil and parent material). Mean value for the total sand fraction has been obtain by combining morphoscopy of each fraction and distribution of the sizes. Sand are mainly composed of sub-angular grains (≈ 80 %) with a significant proportion of round frosted (≈ 10 %).

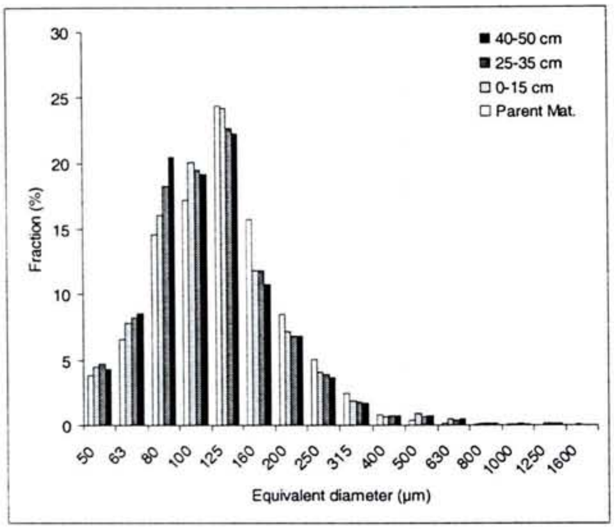


Figure 1: Particle size distribution of specimens sand fraction.

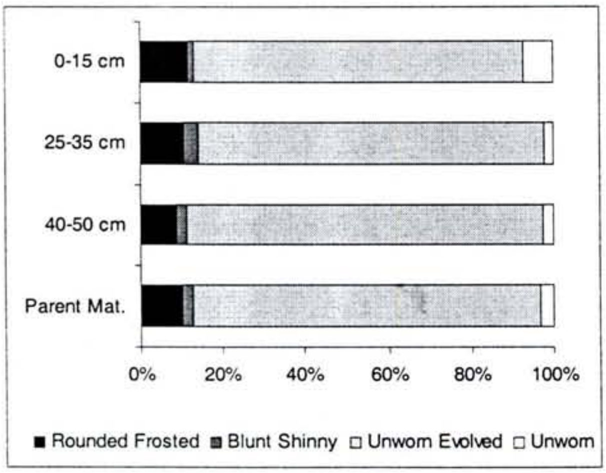


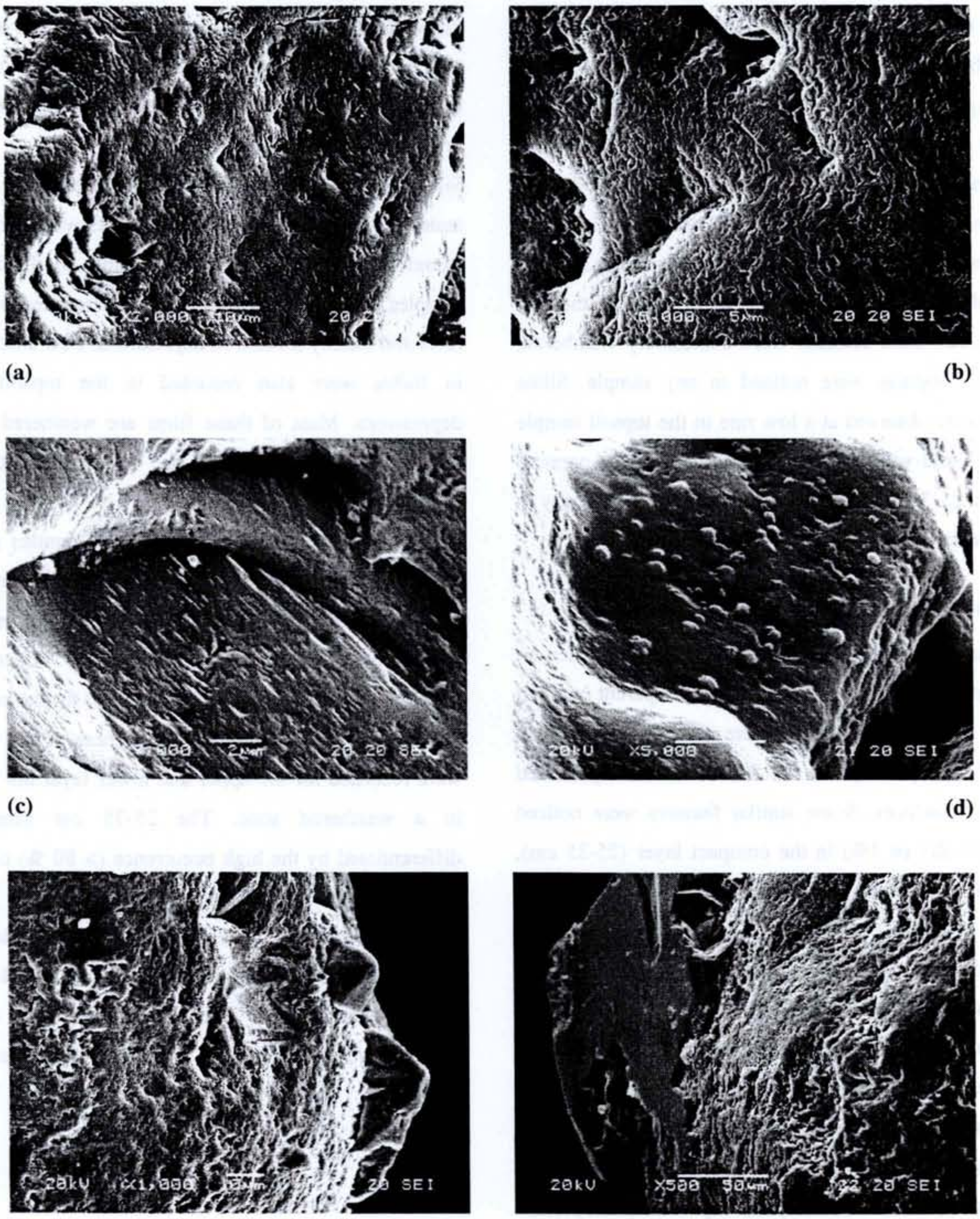
Figure 2: Morphoscopy of quartz grains. Classification into four classes as a function of roundicity.

Quartz grains microtextures

Selected features observed in our samples are illustrated in Figure 3. Mechanically induced impacts of various size and shape are usually imbricate and overlap on the grain surface as shown on plate (a). V-marks of about 10 µm were dominant, abrasion edges (on the left top and bottom), crescent- and cupule-shaped crack were associated in a lower proportion. plate (b) show the surface of the grain at higher magnification (×5,000), all the surface was affected by a multitude of micrometric impact (very small V-marks and crescent-shaped crack). This surface microtexture commonly called "fingernail impacts" is responsible of the frosted aspect of the quartz grains observed at low magnification (stereo microscope). All impacts were weathered (by contrast to the angular impacts that can be seen on some recently transported material).

Plate (c) is a didactic example of dissolution features commonly observed on the soil quartz grains. Geometrical dissolution is composed of small triangular etch pits (< 1 µm). The geometrical aspect of the pits is due to the cristallinity of the quartz. When dissolution is more intense, we observe anastomosed dissolution features. Plate (d) presents a representative overview of fresh silica precipitation observed in our samples. Globular silica appeared as small dots (< 1 µm) in a depression of the quartz grain. When coalescent, the formation of silica flowers start as we can see on the left bottom of the depression.

Plate (e) presents some quartz neogenesis features. The geometrical shape indicate the cristallinity of these features. Finally, plate (e) presents an example of contact surface developed on a grain. All these features are subjected to weathering and erosion by transportation and therefore were recorded as fresh (this picture) or weathered.



(a) (b) (c) (d) (e) (f)

Figure 3: Quartz grain microtextures (Ban Phai soil profile). (a) and (b) aeolian mechanical impacts; (c) oriented dissolution; (d) fresh silica globules ; (e) neogenesis of quartz; (f) contact surface.

Mechanically induced features

Table 2 presents the main mechanically induced features. Conchoidal fractures, V-marks, crescent-shaped cracks, cupule-shaped cracks and abrasion edges were observed at high rate in all samples (Figure 3-a,b). The highest frequencies were recorded for crescent-shaped cracks. Impact rate were quite variable between samples but considering the usual high variability in mechanical impacts induced by transportation, the samples can be considered as similar. Crushing features were observed only in the top 35 first cm of the soil profile. All these features were exclusively weathered, no fresh impacts were noticed in any sample. Silica flakes were observed at a low rate in the topsoil sample (< 2 %) and were much more frequent in the parental material (> 35 %). Desquamation was observed only in the parental material.

Dissolution features

Dissolution features were observed with high rates on soil samples but were not noticed on the parent material (Table 3). Chemical digging were observed on less than 2 % of the topsoil quartz (0-15 cm), exclusively located on plane surfaces. Some similar features were noticed anecdotically (< 1%) in the compact layer (25-35 cm), both on the surface and in depressions, and were filled with siliceous globular. However, Anastomosed networks and geometrical features (small orientated triangular pits) of dissolution were observed with high rates in all soil depths (Figure 3-C). These dissolution features affected principally the topsoil and the subsoil, lower rates were recorded for the compact layer where Anastomosed network and geometric features of dissolution are confined respectively to the plane surface and in the depressions. The highest rate of geometric dissolution was recorded for the subsoil sample where more than 70 % of the quartz were affected, and 10 % of them presented the feature on the plane surface also.

Precipitation features

Siliceous globules (Figure 3-D) and silica flower were observed only in the 25-35 cm soil sample (Table 4). Siliceous globules were always fresh, composed of silica only and located anywhere on the grain. Flower of silica were fresh also, located in the depressions and presented orthogonal patterns (Le Ribault, 1977).

Silica films were observed with high rates in the parent material, both flows and flakes variants were located in summits, faces and depressions (Table 5). In the soil samples, silica film in flows were also recorded, at lower rates and mainly located in depressions. Few silica films in flakes were also recorded in the topsoil grain depressions. Most of these films are weathered in the parent material, all of them are weathered in the soil (Table 5).

Neogenesis of quartz (Figure 3-E) and contact surface (Figure 3-F) were observed in soil samples but none of these features were recorded in the parent material (Table 6). The percentage of quartz affected by neogenesis was extremely high (> 90 %) for the compact layer (25-35 cm). Significant occurrences of this feature were recorded for the upper and lower layer but always in a weathered state. The 25-35 cm sample is differentiated by the high occurrence (> 80 %) of small crystals located mainly in the depression.

Surface of contact (Figure 3-F) were also recorded with higher rate in the compact layer (nearly 50 %). This layer present also 10 % of quartz with fresh contact surface, when other layer presented only weathered features.

Table 2: Mechanically induced impact occurrences on quartz grains. Values are percentage of quartz grain affected by the microtexture features.

	Soil Profile (Ban Phai)			**Parent**
	0-15 cm	**25-35 cm**	**40-50 cm**	**Material**
1. Conchoidal Fractures	**2.0**	**16.6**	**16.1**	**2.1**
Angular	-	-	-	-
Slightly blunted	2.0	16.6	16.1	2.1
2. V-marks (1-150 µm)	**45.6**	**56.9**	**68.9**	**24.6**
Angular	-	-	-	-
Slightly polished	45.6	56.9	68.9	24.6
3. Crescent-shaped Cracks (1-300 µm)	**84.0**	**72.3**	**92.6**	**97.8**
Angular	-	-	-	-
Slightly polished	78.4	72.3	92.6	93.7
4. Cupule-shaped Cracks (3-400 µm)	**23.8**	**30.1**	**56.2**	**69.0**
Angular	-	-	-	-
Slightly polished	23.8	30.1	56.2	69.0
5. Abrasion Edges	**67.1**	**49.6**	**87.0**	**71.0**
Angular - Sub-parallel	-	-	-	-
Angular - Embedded				
Slightly polished - Sub-parallel	61.5	49.6	76.6	71.0
Slightly polished - Embedded	19.6	8.7	57.2	4.1
6. Crushing Features	**5.6**	**7.0**	**-**	**-**
Angular	-	0.1	-	-
Slightly polished	5.6	6.8	-	-
7. Silica flakes	**1.7**	**-**	**-**	**35.3**
8. Desquamation	**-**	**-**	**-**	**4.2**

Table 3: Dissolution features occurrences on quartz grain. Values are percentage of quartz grains affected by the microtexture features.

	Soil Profile (Ban Phai)			**Parent**
	0-15 cm	**25-35 cm**	**40-50 cm**	**Material**
1. Chemical Digging	**1.7**	**0.3**	**-**	**-**
Summits	-	-	-	-
Plane surfaces	1.7	0.1	-	-
Depression	-	0.3	-	-
Filled up with siliceous globules	-	0.1	-	-
2. Anastomosed Dissolution Network	**42.9**	**18.4**	**25.6**	**-**
Summits	8.0	-	3.3	-
Plane surfaces	38.3	18.4	22.2	-
Depression	5.6	-	-	-
Filled up with siliceous globules	-	-	-	-
3. Geometric Dissolution Features	**45.8**	**8.5**	**71.8**	**-**
Summits	-	-	-	-
Plane surfaces	0.5	-	10.6	-
Depression	45.6	8.5	68.5	-
Filled up with siliceous globules	-	-	-	-

Table 4: Precipitation features: Globular silica precipitation and flower of silica features occurrences on quartz grains. Values are percentage of quartz grain affected by the microtexture features.

	Soil Profile (Ban Phai)			**Parent Material**
	0-15 cm	**25-35 cm**	**40-50 cm**	
1. Globular Silica Precipitations	**-**	**7.9**	**-**	**-**
Fresh Globules	-	7.9	-	-
Summits	-	*5.4*	-	-
Plane surfaces	-	*5.4*	-	-
Depressions	-	*2.5*	-	-
Exclusively composed of Si	-	*7.8*	-	-
Weathered Globules	-	-	-	-
2. Flower of Silica	**-**	**5.6**	**-**	**-**
Fresh Flowers	-	5.6	-	-
Hexagonal patterns	-	-	-	-
Orthogonal patterns	-	*5.6*	-	-
Weathered Flowers	-	-	-	-

Table 5: Precipitation features: Silica film in flows and in flakes. occurrences on quartz grain. Values are percentage of quartz grains affected by the microtexture features.

	Soil Profile (Ban Phai)			**Parent Material**
	0-15 cm	**25-35 cm**	**40-50 cm**	
1. Siliceous Film in Flows	**43.2**	**19.2**	**27.0**	**57.1**
Fresh	-	-	-	-
Weathered	43.2	19.2	27.0	57.1
Summits	*2.5*	-	*1.9*	*28,6*
Plane Surfaces	*20.1*	*0.3*	*7.2*	*28,6*
Depressions	*31.4*	*19.0*	*25.2*	*28,6*
2. Siliceous Film in Flakes	**5.6**	**-**	**-**	**73.2**
Fresh	-	-	-	13.5
Summits	-	-	-	*6,4*
Depressions	-	-	-	*7,2*
Weathered	5.6	-	-	73.1
Summits	-	-	-	*49,4*
Plane Surfaces	-	-	-	*29,1*
Depressions	*5.6*	-	-	*25,7*

Table 6: Precipitation features: Neogenesis of quartz and Contact surfaces. occurrences on quartz grain. Values are percentage of quartz grains affected by the microtexture features.

	Soil Profile (Ban Phai)			Parent
	0-15 cm	25-35 cm	40-50 cm	Material
1. Quartz Neogenesis	**23.9**	**91.4**	**51.8**	**-**
Fresh	0.3	80.8	-	-
Tears of quartz	-	*1.1*	-	-
Pseudo-polygonal Neogenesis	-	*0.1*	-	-
Small crystals on plane surface and depressions	-	*4.4*	-	-
Small crystals exclusively in depressions	*0.3*	*80.6*	-	-
Weathered	23.9	57.4	48.5	-
Automorphic obliterating the grain	*2.2*	-	-	-
Small crystals obliterating the grain	*1.7*	-	-	-
Tears of quartz	-	-	*0.2*	-
Pseudo-polygonal Neogenesis	-	-	*3.3*	-
Affecting all the grain	-	*38.8*	*30.8*	-
Small crystals on plane surface and depressions	*2.8*	*11.0*	-	-
Small crystals exclusively in depressions	*13.5*	*1.1*	*33.1*	-
Affected by dissolution features	-	-	27.5	-
2. Surface de contact	**37.6**	**49.0**	**22.1**	**-**
Fresh	-	10.1	-	-
Weathered	37.9	37.8	22.1	-
Summits	35.4	41.4	16.7	-
Plane Surfaces	1.7	35.6	12.8	-

Discussion

Parent material inheritance

Parent material consisted predominantly of fine and very fine sand, with a mode between 125 and 160 µm. Quartz grains are mainly angular, with a significant proportions of round frosted grains. Microtexture analysis revealed many mechanically induced features, as conchoidal fractures, V-marks, crescent- and cupule-shaped cracks and abrasion edges, that indicate high energy transportation in dry conditions. Silica flakes and associated desquamation are also common in such dry energetic transportation (Le Ribault, 1977). Such mechanically induced microtextural features are evidences of aeolian activity (Newsome and Ladd, 1999). These results confirmed speculation of Sanderson *et al.* (2001) concerning aeolian activity in the region but a low energy subsequent mobilisation is not excluded as aeolian impacts are all highly weathered and polished. If transportation post deposit occurred, it was not high energy in water conditions, as the occurrence of blunt shinny quartz is nearly null.

The soil samples presents the same distribution and morphoscopy of sands. The transport impact (mechanically induced microtextures) are similar also, with the exception of silica flakes and desquamation, that are susceptible to being weathered during a long pedagogical mobilisation (Le Ribault, 1977). These results confirm that the parent material sample is well representative of the soil origin. Sand size distribution, morphoscopy and mechanically induced microtextures of the soil are inherited from the parent material.

Pedogenetic evolution tendencies

Beyond microtexture features similar to parent material, quartz grains of the soil showed a combination of chemical dissolution and precipitation features inexistent in the parent material. Characteristics of dissolution include etch patterning, triangular shaped etch pits and solution features. Precipitation forms include globules, silica flower, neogenesis and preserved grain contact faces The combination of dissolution and precipitation of the soil profile compare to the original material suggested that precipitation and dissolution was mainly post deposit. Through the long period of pedogenetic mobilisation, surface remobilisation under low energy is not to exclude, but evolution of the material was in situ as no fresh transport marks were observed.

Precipitation and dissolution as a function of depth

Figure 3 presents percentage of quartz grains affected by dissolution or precipitation independently of the feature variant; Precipitation features excepted the one attributed to parental material inheritance. We observe that both dissolution and precipitation are well represented in all depths, however, it appeared that topsoil and subsoil were mostly effected by dissolution, whereas the compact layer was the most affected by precipitation features.

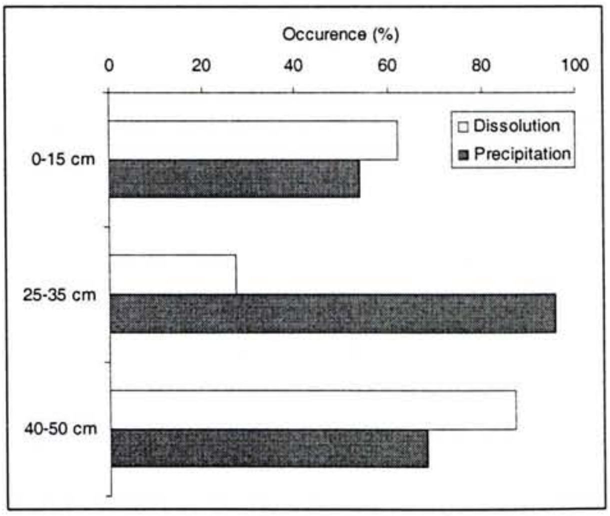


Figure 4: Dissolution and precipitation as function of the depth (Ban Phai soil profile). Values are percentage of the quartz grains affected by at least one feature.

If we look now at the precipitation freshness, it appears that weathered states of neogenesis, contact surfaces and silica flakes had similar frequencies in all depths. However, that is the fresh precipitation features that induced the differences in global frequencies. Globular silica were observed only in the compact layer, and then their general occurrence is not high (2 % of the grains) but they were observed systematically on coarse sand, they were always fresh and precipitated in depression of the grains. Flower of silica which is the next step of coalescent globular silica were also fresh. Globular silica and silica flower are the first steps of precipitation. Amorphous silica use to precipitate first as globular, more and more coalescent, and forming silica flowers (Le Ribault, 1977).

Implication of these results

Quartz microtextures inherited from the parental material are a key explanation of the high resistance to penetration observed in the field. Fine angular sand and silt arrangement would result in a very cohesive material as suggested by Bruand *et al* (2004). Microtexture inherited from transportation would act in the same way as soil strength increased since particle shape deflect from the spherical form.

Microtexture features peculiar to soil samples indicate the intense dynamic of silica in the soil profile. This processes did not result in strong cementation of the grain as observed in other regions, but features as quartz neogenesis and contact surface may increase the resistance to penetration of the material.

Variation of respective intensities of dissolution and precipitation as a function of depth suggest that the phenomenon of silica precipitation is still active in the soil profile as the field as been ploughed initially to 40-cm depth. Moreover, these results suggest that tillage may be a factor affecting the silica dynamic. Silica will precipitate when the concentration of silica in the solution increases (i.e. evaporation of pure water). Precipitation occurs usually in depression, first as silica globules and then flowers, but may occur also between quartz grains when these are organised in a close arrangement (Le Ribault, 1977). The compact layer is characterised by a close arrangement of grains (Bruand *et al.*, 2004), and one can deduce this layer may be the ideal location for solution drying and therefore precipitation to occur.

However, another explanation to depth of precipitation is the constant flux of capillary rise from the lower part of the profile (Lesturgez *et al.*, 2001). Solution is probably charged in silica and the change of phase, liquid to vapour, occurring in the compact layer (the top soil is frequently tilled and dry) would explain the accumulation of silica in this layer. Dissolution of phyllosilicates is a source of amorphous silica in such acid soil (Lesturgez *et al.*, 2003).

Conclusion

The study of quartz grains characteristics and especially microtexture features revealed that properties inherited from the parent material are consistent with a high resistance to penetration due to packing, filling and friction between grains. The features acquired through the pedogenetic evolution tend globally to increase again the strength potential of the material as specific feature such as contact surface, increase the contacts between grain and lock the system. Nowadays, the silica dynamic seems still active as fresh precipitation is overlaying weathered features. This newest precipitation is mainly localised in the compact layer, suggesting that later modification of the soil profile influence the precipitation sites. Intense weathering on the surface and mobilisation of silica through dissolution of clay minerals are abundant sources of amorphous silica. Close arrangement of grains and brutal changes of hydraulic properties in the compact layer would favour the precipitation there. The changes of phase of solution coming up by capillary rise also occur in the compact layer and may be involved in the precipitation processes.

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Annexe 6

Structural amelioration of a sandy soil by slotting technique

Christian Hartmann, Grégory Lesturgez, Pramuanpong Sindhusen & Santi Ratana-Anupap

Amélioration structurale d'un sol sableux par la technique du rainurage

Le rainurage s'est avéré être une technique de travail du sol efficace pour améliorer l'enracinement et les rendements des cultures dans les sols sableux du Nord-Est Thaïlandais. La présence d'un horizon compact entre 20 et 40 cm de profondeur est l'un des principaux facteurs limitant la production végétale. Les autres techniques de travail du sol telles que le sous-solage ont échoué dans la mesure ou le sol se tasse à nouveau après la première pluie conséquente. Une étude au laboratoire combinant micromorphologie, rétention d'eau et porosité mercure a été conduite de manière à rendre compte des modifications structurales persistant 2 ans après le rainurage. Plusieurs modification de la porosité et de l'organisation de la phase solide ont ainsi pu être mis en évidence, et expliquent la prolifération des racines dans les rainures. La formation de large macropores et surtout la continuité de cette porosité avec l'horizon sous-jacent constitue une première amélioration de la structure massive défavorable. Des modifications touchant la porosité la plus fine ont également été mises en évidence. Cette gamme de porosité induite par un arrangement très serré des constituants a diminué dans la rainure. En raison de l'amélioration structurale et de la durabilité de ses effets, le rainurage est une technique prometteuse dans ce type de sols sableux et instables.

Structural amelioration of a sandy soil by slotting technique

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Abstract

Slotting has proved to be an efficient tillage technique in ameliorating rooting depth and yields of crops in sandy uplands of Northeast Thailand. The presence of a compact layer located between 20 and 40 cm depth is one of the limiting factor of vegetal production and other tillage techniques as deep ploughing failed as the soil recompacts after the first heavy rain. A laboratory study combining micro-morphology, water retentions and mercury porosimetry has been conducted in order to investigate structural changes remaining two years of slotting. Several change in the porosity and organisation of the solid phase have been highlighted as explanation of the root proliferation in the slots. The formation of large macroporosity and the continuity of the porosity with the underneath layer constituted a first amelioration of the unfavourable massive structure. Changes in the smallest porosity highlighted also that the tight organisation of the constituents responsible of high resistance to penetration was partially modified. Because of structural amelioration and longstanding of the effect, slotting appears as a promising tillage technique is such sandy unstable soils.

Introduction

Light textured sandy soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the Northeast Thailand uplands (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 2 cmolc kg^{-1}) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999).

However, soil compaction and the generalised presence of a highly resistant layer at low depth appeared to be the main limiting factor to plant production (Bruand *et al.*, 2004). Root confinement within a small soil volume hinder nutrient and water uptake where both are in limited supply. Subsoiling and deep ploughing have not effectively overcome this dense layer. However localised intervention as slotting (Jayawardane *et al.*, 1995) or vertical mulching (Meyer *et al.*, 1992) have proved to be efficient tillage techniques on sandy soils. A simple slotting intervention proved to increase significantly rooting depths and yields of various crops in Northeast Thailand. Moreover benefits remained at least 1.5 years through the introduction of slots (Hartmann *et al.*, 1999).

However, in order to optimise the practice and predict its effects on rooting, a better understanding of structural modifications induced by the technique is need. The aim of this study was to investigate soil organisation and porosity modification induced by the slotting technique. Three different methods were used to assess the porosity at different scales (i.e. micromorphology, water retention and mercury porosimetry).

Materials and methods

Site characteristics and soils.

The study was conducted in Northeast Thailand at the Land Development Department research station located 15 km from Nakhon Ratchasima, Korat province (15°N, 102°E). The choice of the site was based on previous studies that highlighted a high resistance to root penetration, particularly in the subsoil (Bruand *et al.*, 2004). Northeast Thailand is characterised by a semi-arid tropical climate with a distinct rainy season from April to October and a dry season from November to March. The average annual rainfall is 1020 mm. Annual and monthly rainfall is highly variable on a year to year basis (min.=599 mm and max.=1446 mm for the period 1971-1998). Rainfall generally exceeds evaporation during the growing season and there are at least 3 months of dry season in the year. Water stress is frequent for most crops, not only during the dry season, but also between the rainfall events, due to the rapid drainage and inherent low water holding capacity of the soil. The soil at the experimental site is of a sandy texture and belongs to the *Nam Phong* soil series (Haimsrichat *et al.*, 1993). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) and Arenic Acrisol (FAO classification). Selected chemical and physical characteristics of the soil are presented in Table 1.

Experimental design

Slotting involves the creation of narrow, parallel bands of tilled soil, loosened to the require depth, leaving the rest of the soil undisturbed (Jayawardane *et al.*, 1995). The slotting characteristics are chosen according to the soil problem which need to be remediated. In our case, narrow slots (10 cm width) were opened under the planting line to a depth of 40 cm in order to bypass the compact layer (Figure 1). For this experiment, slotting was done manually to avoid mixing of the topsoil and subsoil. After slotting, the topsoil was disk-ploughed with a motorised cultivator. Maize (*Zea mays* cv. SW 3601) was established at a density of 50,000 plants ha-1 with an average of 3 plants per stand on ridge.

Table 1: Selected soil physical and chemical properties of the Arenic Acrisol at the study site.

Depth (cm)	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in μm*								OC (%)	CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1000	1000-2000	2000-5000			Mean	SD
10-15 cm	37	63	60	381	357	81	19	2	0.19	0.9	1.48	0.07
25-35 cm	53	64	61	399	331	75	17	<1	0.17	1.2	1.69	0.05
40-50 cm	88	65	69	347	324	96	11	<1	0.08	2.3	1.67	0.05

OC is organic carbon content, CEC is cation-exchange capacity, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n=5).

Field measurements and sampling

Main agronomical characteristics including root systems descriptions and yields of crops were discussed previously (Hartmann *et al.*, 1999). Undisturbed samples were collected in the tilled layer (0-15 cm), in the compact layer (25-35 cm), in the adjacent slot (25-35 cm) and in the loose layer below (40-50 cm) as presented on Figure 1. Bulk density (measured by the cylinder method) was slightly lower in the slot (1.67 Mg m^{-3}) than in the compact layer (1.72 Mg m^{-3}).

Image analysis

Undisturbed samples (12×6×4 cm^3) were oven-dried at 40°C for a week and impregnated with polyester resin that was diluted with styrene monomer (30 % by volume) at room temperature under low vacuum (5 kPa). A hardener and a fluorescent compound (Uvitex OB, Ciba, Geigy, Hawthorne, NY) were added to the resin mixture in the amount of 1 $g.L^{-1}$ (Hartmann *et al.*, 1992). Resin polymerisation and hardening were complete after about 4 weeks. Thin sections of approximately 30 µm in thickness were prepared based on quartz interference colours. For each thin section, three images (7.7×5.7 mm) were taken under UV light . The resolution of the pictures was 10 µm per pixel. After classical description, porosity characteristics were measured using the Visilog™ image analysis software. The equivalent diameter was measured by progressively filling the pores with hexagonal structuring elements of increasing size. The pores were classified according to a shape index related to their size (area) and shape ($perimeter^2$ / 4×area).

Water retentions

We measured the specific water content (W_f, in g of water per g of oven-dried soil), and the specific volume of the clods at field conditions (V_f, in cm^3 per g of oven-dried soil) using the kerosene method (Monnier *et al.*, 1973). Specific water content (W, in g of water per g of oven-dried soil) at water potentials, Ψ, of -10, -33, -100, -330, -1000 and -16 000 hPa was measured using pressure membrane or pressure plate apparatus. Clods were placed on a paste made of < 2-µm particles of kaolinite to establish continuity of water between the clods and the membrane or the porous plate of the apparatus (Bruand *et al.*, 1996). At –16 000 hPa water potential we also measured the specific volume of the clods ($V_{16\,000}$, in cm^3 per g of oven-dried soil) as we did with the clods at field conditions. Specific water content and volume were expressed with respect to the dry mass of the sample after oven-drying at 105°C for 24 h. Fifteen clods were used for each sample to determine the mean values of V_f, $V_{16\,000}$, W_f and W at the different values of water potential. Water ratio (θ) and void ratio (e) derived from these data are expressed as a function of equivalent constriction diameter (Tessier, 1975).

Mercury porosimetry

Mercury porosimetry involves measurement of the

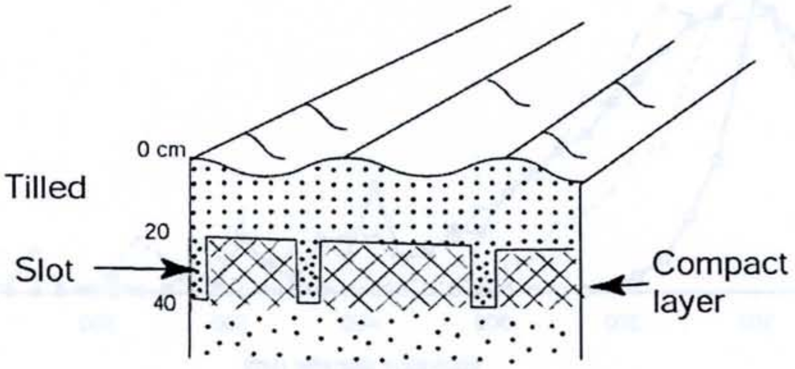

Figure 1: Schematic representation of the soil profile, slot pattern and sampling.

pressure required to force mercury into the pores of a dry sample and of the volume of intruded mercury at each pressure (Fiès and Bruand, 1998). Mercury intrusion was performed with a porosimeter (Micromeritics 9320, Mönchengladbach, Germany) which operated from a pressure of 4 kPa up to a maximum of 2000 kPa, enabling pore-size distribution study for pores with equivalent diameters (D_e) ranging from 360 down to 0.006 µm, respectively. Values for the surface tension of mercury and its contact angle on soil material were 0.484 N m^{-1} and 130°, respectively. Small clods (1–2 cm^3 in volume) were selected and dried at 105°C for 24 h before mercury injection. Three clods were measured for each horizon.

Results

Pore size distribution

The pore size distribution was unimodal in all samples (Figure 2). The compact layer appeared very different when compare to the upper and lower layer with the mode at 100 µm and without pore larger than 200 µm. The three replicates gave very similar results that demonstrate the high homogeneity of this layer. The tilled layer presented less porosity in the 50-100 µm range but more in the 100-300 µm range. Very few pores were larger than 300 µm. The loose subsoil (40-50 cm) was the sample presenting the largest porosity with pore up to 800 µm. In the slot, the mode was higher (150 µm) than in the compact layer and the curve shape was similar to the loose layer below. Some poroids had an equivalent diameter larger than 400 µm. The three replicates showed the same trends but they were not similar because of a higher heterogeneity in the arrangement of the solid particles.

Pore typological repartition

Compared to the compact layer, the pore surface in the slot was increased by 80 %. This increase was mainly related to large pores (> 500,000 μm^2) which did not exist in the compact layer. These pores represented one-third of the total pore surface in the slot sample. Medium pores (50,000-500,000 μm^2) also increased in the slot sample compare to the compact layer sample (Figure 3-a). Surface related to all shape type of pore increased but the increase was the most obvious for elongated pores (shape index value > 15). This pore type were quasi absent both in the compact layer and in the tilled topsoil,

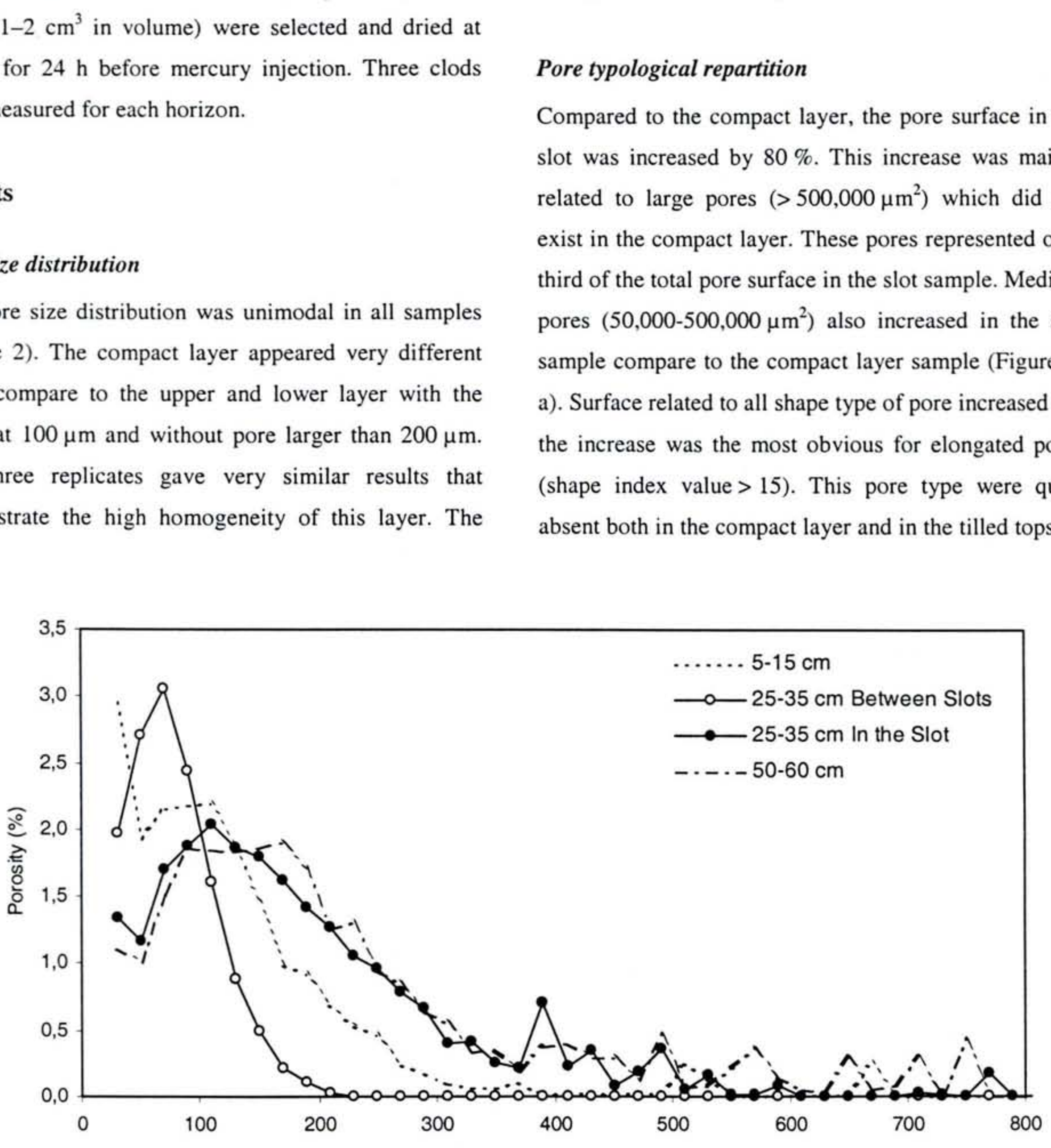

Figure 2: Pore size distribution from image analysis.

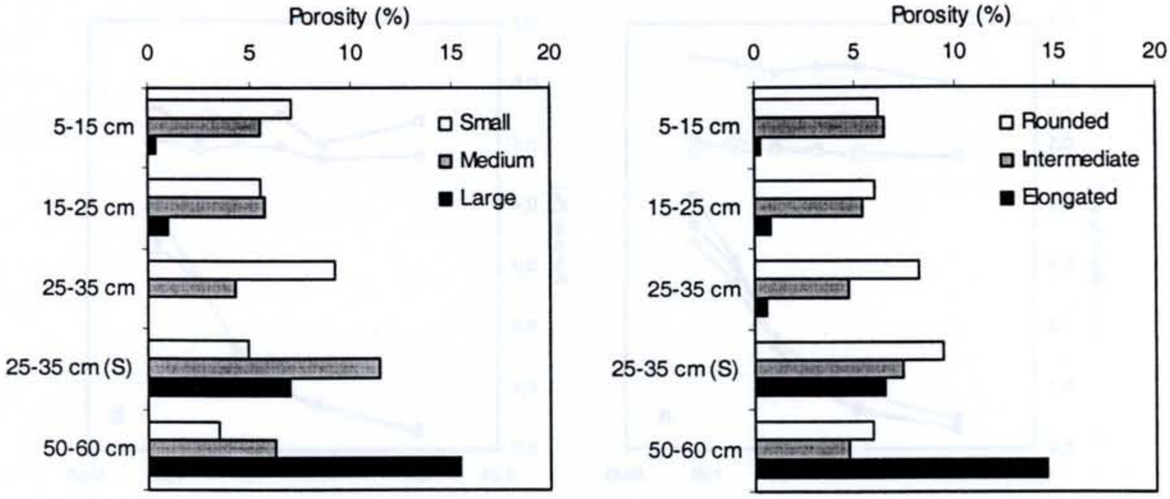

Figure 3: Pore typological repartition: (a) as a function of area, (b) as a function of shape.

but were the main component of the subsoil porosity (Figure 3-b).

Water retention curves

Water and void ratio are presented in Figure 4 as a function of constriction diameter. Void ratio (e) did not change significantly as a function of potential for any samples; The tilled layer (0-15 cm) presented much more void than the other samples (Figure 4-a). However, θ was significantly higher only for pores of equivalent diameter > 100 µm. Slot and no-slot samples did not presents significant difference in void ratio, and water ratio was higher only for pore of equivalent diameters > 100 µm (Figure 4-b).

Mercury porosimetry

The total pore volume measured by mercury porosimetry ($V_{p,m}$) was significantly higher for the slot samples (0.201 cm^3 g^{-1}) compared to the compact layer samples (0.167 cm^3 g^{-1}). Cumulative intrusion curves and their derivative curve (Figure 5) showed that the total pore volume resulted from the contribution of three classes of pores that were denominated by Pore A, B and C (Bruand *et al.*, 2004). The class of pore A had a modal equivalent-pore diameter ($D_{e,A}$) of 27 µm for both slot and compact layer (Figure 5-b). However, the shape of the peak was much sharper for the compact layer samples. This class of pores contributed 86 to 84 % to $V_{p,m}$. respectively in the slot and compact soil. Compact layer samples showed a second entry of mercury corresponding to the class of pores B with $D_{e,B}$ around 0.6 µm. This entry was also detected in the slot samples but was much lower and less obvious as there was no clear peak. This class of pores contributed 11 to 13 % to $V_{p,m}$. respectively in the slot and compact soil. Finally, there was a third entry of mercury corresponding to the class of pores C. ($D_{e,C}$) was smaller than 0.006 µm (Figure 5-b).

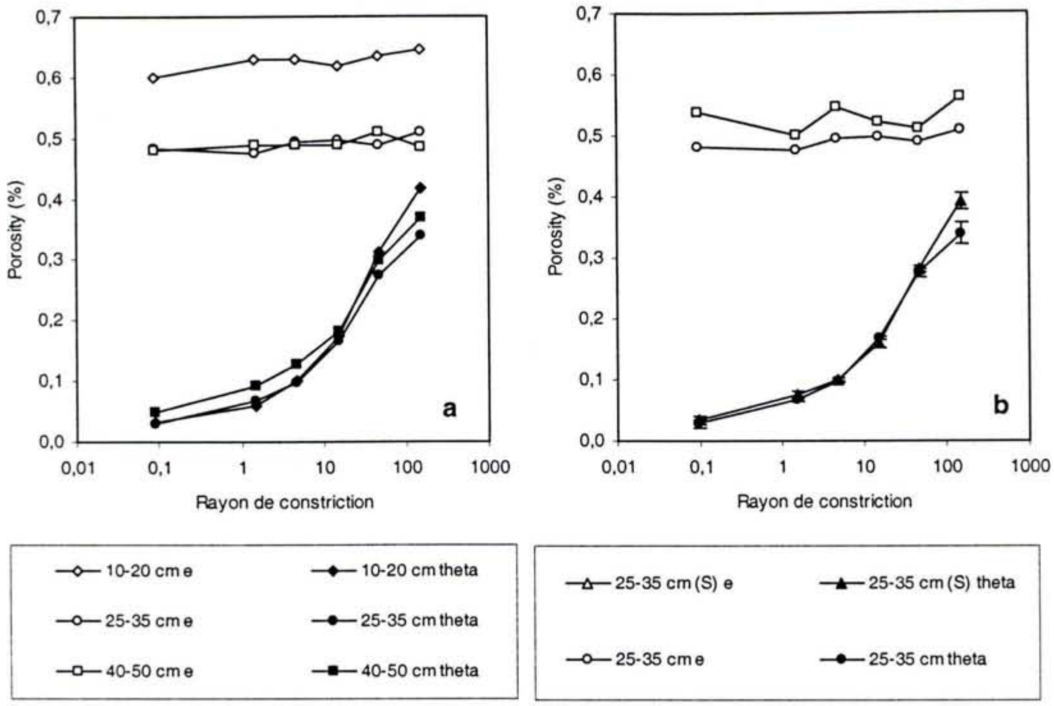

Figure 4: Water retention (θ) and void ratio (e) as a function of depth (a) and comparison slot / no-slot (b).

Discussion

Porosity of the original soil profile

The compact layer appeared as a singular organisation layer in the soil profile (Figure 2). While the tilled layer (5-15 cm) included a large range of macropores mechanically induced and the subsoil (50-60 cm) a larger range of macropores, partially biologically induced, the compact layer (25-35 cm between slots) presented a restricted range of macropores and pores larger than 200 µm are absent. The typological distribution of pores (Figure 3) highlighted also that the compact layer appears as a singular layer. Shapes of pores were similar to the topsoil (Figure 3-b) but there were no large macropores in this layer (Figure 3-a). Water retention curves highlighted also the difference of total porosity between the tilled layer (0-15 cm) and the layers underneath (Figure 4-a). However, θ was significantly higher only for pores of equivalent diameter > 100 µm. These results confirmed by a physically different method that only the largest pores are involved in the difference of total porosity. All these results suggested that the compact layer, located between 20 and 40 cm depth, constitute not only a physical limit because of its density and resistance to penetration (Bruand *et al.*, 2004) but also because of the break in the continuity of large macroporosity. Since it has been shown that root proliferation are correlated both to resistance to penetration (Panayiotopoulos *et al.*, 1994; Bengough *et al.*, 1997) and presence of large macropores (Volkmar, 1996; Stewart *et al.*, 1999), these results confirmed results of Bruand *et al.* (2004) and explained why this layer is a dramatic limit for root systems of most crops.

Macroporosity induced by slotting

When the compact layer has been slotted (25-35 cm in slots, Figure 2), pore distribution changed drastically, the porosity smaller than 100 µm tended to decrease and a large range of pores up to 600 µm appeared. After such modification, the pore distribution of slotted layer was similar to the one of the lower layers (Figure 2).

The gain of total porosity was therefore mainly induced by the formation of large pores (Figure 3-a). The shape distribution of the pores changed also: the compact layer was constituted of very few elongated pores, just as the tilled layer and opposite to the deeper layers. After slotting, a third of the porosity was attributable to elongated porosity (Figure 3-b). Water retention curves confirmed also the difference of total porosity between slot and no-slot were mainly related to pores > 100 µm of equivalent diameter (Figure 4-b). These results suggest that by the way of slotting, the continuity of large macroporosity was restored. The slot part of the layer 25-35 cm layer does not appear any more as a break in the continuity of macropores.

Porosity and fabric

Our results shown three classes of pores for the studied soil (Figure 5). The class A corresponds to the arrangement of sand particles alone. This class increase significantly resulting a new organisation of the sand particles. The class B, reported by Bruand *et al.* (2004) as the pores within the clusters of fine material present between the sand grains, and considered in their study as the main source responsible of high resistance to penetration of the soil, has slightly decreased in volume (Figure 5-b). This pore volume decrease, highlighting a less packed arrangement of grain, would explain a decrease in soil strength in the slot and the proliferation of roots in this volume.

Conclusion

Slotting has proved to be an efficient technique from an agronomic point of view. Increasing rooting depth, this tillage technique is longstanding and increase significantly yields. Root proliferation in the slot is assumed to be the main factor of success of the practice. Our study highlighted several changes both in the porosity and organisation induced by slotting and which tends to explain this proliferation. The compact layer which developed at low depth (20-40 cm) is a limit for rooting depth because of its high resistance to penetration and the absence of macropores in its massive structure. Slotting technique induce the creation of large macropores as other tillage technique at the difference that the slotting induced macropores are still obvious after 2 years. The slot layer does not appear any more as a porous media drastically different of the underneath subsoil and continuity of large macropores is assured. In other hand, slotting induce changes in the very small porosity related to the arrangement of particles. The range of porosity involved in the high resistance to penetration tends to decrease. It is also a note that slotted layer did not recover the massive structure as tilled layer usually does. It is assumed that preservation of the compact layer between slots helped to maintain a loose organisation of the soil by bearing pressures of the topsoil and induce by machinery.

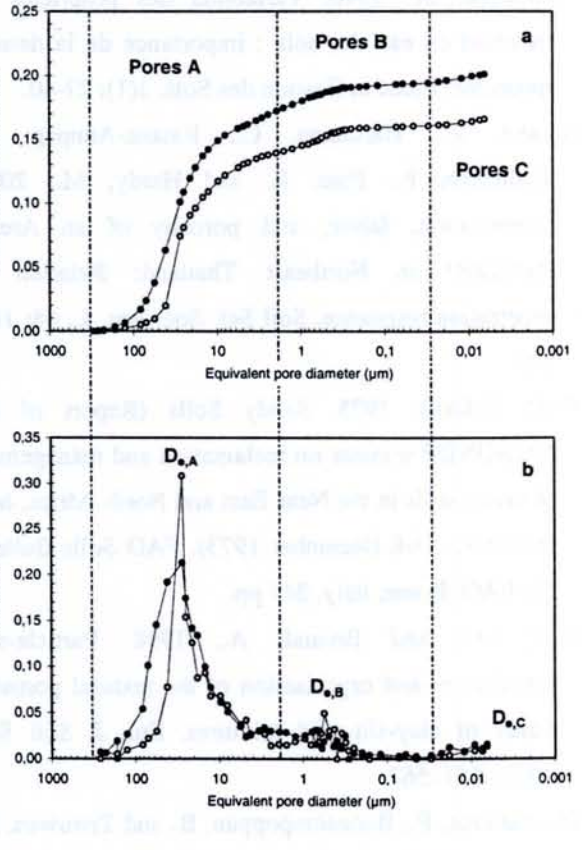

Figure 5: Mercury intrusion results recorded for the slot (–●–) and no-slot (–○–) samples (25-35 cm): (a) mean cumulated pore volume curve, (b) derivative curve.

Acknowledgments

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Annexe 7

Roots of *Stylosanthes hamata* create macropores in the compact layer of a sandy soil

Plant and Soil, Volume 260, Issue 1-2, March 2004, Pages 101-109.

Grégory Lesturgez, Roland Poss, Christian Hartmann, Emmanuel Bourdon,
Andrew Noble & Santi Ratana-Anupap.

Les racines de **Stylosanthes hamata** *créent des macropores dans l'horizon compact d'un sol sableux.*

Cet article présente les résultats d'une expérimentation au champ conçue pour évaluer l'utilisation potentielle de la légumineuse Stylosanthes hamata *(stylo) pour améliorer la structure d'un horizon compact dans un sol sableux du Nord-Est Thaïlandais. Les sols sableux acides fréquents dans le Nord-Est Thaïlandais ont un potentiel agronomique réduit du fait de leurs propriétés chimiques et physiques. Un horizon compact à 20-40 cm réduit l'enracinement de la plupart des cultures, et réduit par conséquent la quantité de nutriments disponibles pour la croissance des plantes. Les labours profonds et sous-solages sont coûteux et ne se sont avérés inefficaces pour remédier au tassement dans la mesure où ces sols sont instables et s'effondrent après la première grosse pluie. Une étude sur trois ans a été conduite de manière à évaluer l'effet d'une culture continu de stylo sur la porosité de l'horizon compact et son influence sur le développement racinaire et les rendements d'une culture de maïs ultérieure. Le stylo a été cultivé de façon continue pendant deux ans dans des parcelles expérimentales et comparé à une rotation stylo-maïs habituellement pratiquée. La distribution des racines et la densité de macropores ont été mesurées sous les deux systèmes de culture. Après 24 mois de stylo continu, les racines ont été capables de pénétrer l'horizon compact, induisant une amélioration significative de la macroporosité de celui-ci. La culture de maïs suivante a développé un système racinaire plus vaste et profond en utilisant les macropores laissés par les 24 mois de stylo continu que dans le cas des rotations stylo-maïs. Cette étude démontre le rôle potentiel de* Stylosanthes hamata *dans l'amélioration des horizons compacts sableux.*

Plant and Soil, Volume 260, Issue 1-2, March 2004, Pages 101-109

Roots of Stylosanthes hamata create macropores in the compact layer of a sandy soil

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Abstract

The paper presents results of a field experiment designed to investigate the potential use of forage legume *Stylosanthes hamata* (stylo) to ameliorate the structure of a compact layer in sandy soils of Northeast Thailand. Sandy and acidic soils that are common to Northeast Thailand have restricted agronomic potential due to inherent chemical and physical properties. A compact layer at 20-40 cm reduces root elongation for most crops, thereby restricting the quantity of nutrients and water available for the plant growth. Deep ploughing and subsoiling are costly and have not been shown to be effective in overcoming compaction since these soils are unstable and collapse after the first heavy rainfall event. A three-year study was conducted in order to evaluate the effect of continuous stylo on the porosity of the compact layer and its influence on root elongation and yield of a subsequent maize crop. Continuous stylo was grown for two years in experimental plots and compared to a currently used stylo-maize rotation. Root distribution and macropore density were measured under the two cropping systems. After 24 months of continuous stylo, roots were able to penetrate the compact layer, resulting in a significant improvement in the macroporosity of this layer. The subsequent maize crop developed a deeper and more extensive root system using macropores created after 24 months of continuous stylo when compared to the stylo-maize rotation treatment. This study demonstrates the potential role of *Stylosanthes hamata* in structural amelioration of sandy compact layers.

Introduction

Light textured soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (Panichapong, 1988). Such soils occupy a significant area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). The vegetation was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils are highly productive in that they support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et* *al.*, 1998).

These soils are often characterised as being of a sandy texture, acidic to depth (pH_{CaCl2} around 4.0) with very low exchange properties (CEC < 2.5 $cmol_c\ kg^{-1}$) and therefore a low nutrient supplying capacity. Similarly, the physical characteristics of these soils are poor with a compact layer often developing at 20-40 cm that prevents root proliferation at depth (Hartmann *et al.*, 1999; Bruand *et al.*, 2004). Whilst this layer restricts root growth it does not prevent the rapid drainage of these soils and therefore does not enhance the water holding capacity as observed in other compact sandy soils (Mamman and Ohu, 1997). Therefore a plant with deep-rooting characteristics could potentially enhance the rooting characteristics of subsequent crops, thereby improving soil nutrient recycling and crop productivity (Salako *et al.*, 2002).

The impacts of soil structure on root growth and proliferation is a topic that has received considerable attention over the past decade (Passioura, 1991; Stirzaker *et al.*, 1996; Angers and Caron, 1998). It has been shown that root proliferation in the soil is closely dependent on the presence of macropores (Hatano *et al.*, 1988; Hatano and Sakuma, 1990; Stewart *et al.*, 1999). Various studies, using artificial impenetrable subsoils containing arrays of cylindrical holes (Dexter, 1986), artificial perforations of a compact layer (Nambiar and Sands, 1992) or artificially-made macropores that simulated vertically oriented bio-pores (Nakamoto, 1997), confirmed the importance of macroporosity in improving root proliferation below compacted layer by subsequent crops. Mechanical modification of the soil profile, through deep-ploughing or subsoiling, is able to significantly increase the porosity of soils. However, such profile modifications require significant inputs of energy that is often beyond the means of resource-poor farmers and invariably, the benefits diminish rapidly after the first heavy rains due to the inherently unstable nature of these soils (Hartmann *et al.*, 2002). Actively growing plant root systems have the potential to ameliorate subsoils in poor physical condition by biological drilling (Cresswell and Kirkegaard, 1995). Decaying roots leave a continuous network of vertically-oriented macropores that the subsequent plants can use (Volkmar, 1996; Angers and Caron, 1998). It has been shown for example, that a severely compacted sandy loam soil can be ameliorated by a cover-crop through the combined effects of organic mulches and root drilling (Stirzaker and White, 1995). At the other extreme of soil texture, Pillai and McGarry (1999) have demonstrated that plant roots were able to improve the structure of a compacted vertisol (roots and wet-dry cycle actions).

Stylosanthes hamata has the ability to significantly increase the number of macropores in long-term tropical legume/pasture mixes through the process of root drilling (Bridge *et al.*, 1983) and is therefore an ideal low-cost method for improving the quality of native pastures and legume-based cropping systems (Miller *et al.*, 1991; Oikeh *et al.*, 1998). In contrast, the growing of *Stylosanthes hamata* in a 3-4 month rotation with a non-legume crop has been shown to increase the nitrogen content of the soil and, therefore supply nitrogen to the subsequent crop, but had no effect in ameliorating soil structure in Northeast Thailand (Ruaysoongnern and Aitken, 1980). This may in part be attributed to the short duration of the legume component since it has been observed that the density of macropores under *Stylosanthes hamata* increases significantly only after several years of permanent pasture (Bridge *et al.*, 1983).

A three year field study was undertaken to investigate the potential role of *Stylosanthes hamata* in ameliorating the structure of a compact layer in a typical light textured soil in Northeast Thailand. The effectiveness of stylo in enhancing the rooting depth of a subsequent maize was assessed with respect to (i) the ability of the species to penetrate a compacted layer, (ii) the creation of macropores by roots into the subsoil and (iii) the benefits to the subsequent maize crop.

Materials and methods

Site characteristics and soils

The study was conducted in Northeast Thailand at the Land Development Department research station located 15 km from Nakhon Ratchasima, Korat province (15°N, 102°E). The choice of the site was based on previous studies that highlighted a high resistance to root penetration, particularly in the subsoil (Hartmann *et al.*, 1999).

Northeast Thailand is characterised by a semi-arid tropical climate with a distinct rainy season from April to October and a dry season from November to March. The average annual rainfall is 1020 mm. Annual and monthly rainfall is highly variable on a year to year basis (min.=599 mm and max.=1446 mm for the period 1971-1998). Rainfall generally exceeds evaporation during the growing season and there are at least 3 months of dry season in the year. Water stress is frequent for most crops, not only during the dry season, but also between the rainfall events, due to the rapid drainage and inherent low water holding capacity of the soil.

The soil at the experimental site is of a sandy texture and belongs to the *Nam Phong* soil series (Haimsrichat *et al.*, 1993). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) and Arenic Acrisol (FAO classification). Selected chemical and physical characteristics of the soil are presented in Table 1. Field measurements of resistance to penetration are presented in Figure 1 along with the gravimetric water content under wet and dry conditions.

Experimental design

The study site has been under an annual cropping regime since clearing of native vegetation that includes ploughing to a depth of approximately 20 cm and the subsequent formation of ridges on which the crop was planted. Beneath the tilled topsoil, field observations indicate the presence of a subsoil with high penetration resistance that decreased with depth (Figure 1).

The study consisted of two treatments, namely, (a) continuous stylo (CS) where *S. hamata* was grown for 24 months before being converted to maize (*Zea mays* cv. SW 3601) production in the third year; and (b) stylo-maize rotation (SM) where *S. hamata* was grown for 4 months, followed by maize for 4 month, followed by a 4 month ley annual weedy pasture over the dry season. The latter treatment represents current farming practice. The experimental design was a randomised complete block design with 10 plots of 48 m^2 in area (8×6 m) for each treatment.

During the maize cropping phase, the soil was ploughed to a depth of 20 cm and ridges 10 cm high and 30 cm wide were formed. Ridging was undertaken to prevent flooding of the crop during heavy rainfall events which are common during the wet season.

Maize was established at a density of 50,000 plants ha^{-1} with an average of 3 plants per stand on ridge. Stylo was established at a density of 30,000 plants ha^{-1} with an

Table 1: Selected soil physical and chemical properties of the Arenic Acrisol at the study site.

Depth (cm)	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in µm*								OC (%)	CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1000	1000-2000	2000-5000			Mean	SD
10-15 cm	37	63	60	381	357	81	19	2	0.19	0.9	1.48	0.07
25-35 cm	53	64	61	399	331	75	17	<1	0.17	1.2	1.69	0.05
40-50 cm	88	65	69	347	324	96	11	<1	0.08	2.3	1.67	0.05

OC is organic carbon content, CEC is cation-exchange capacity, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n=5).

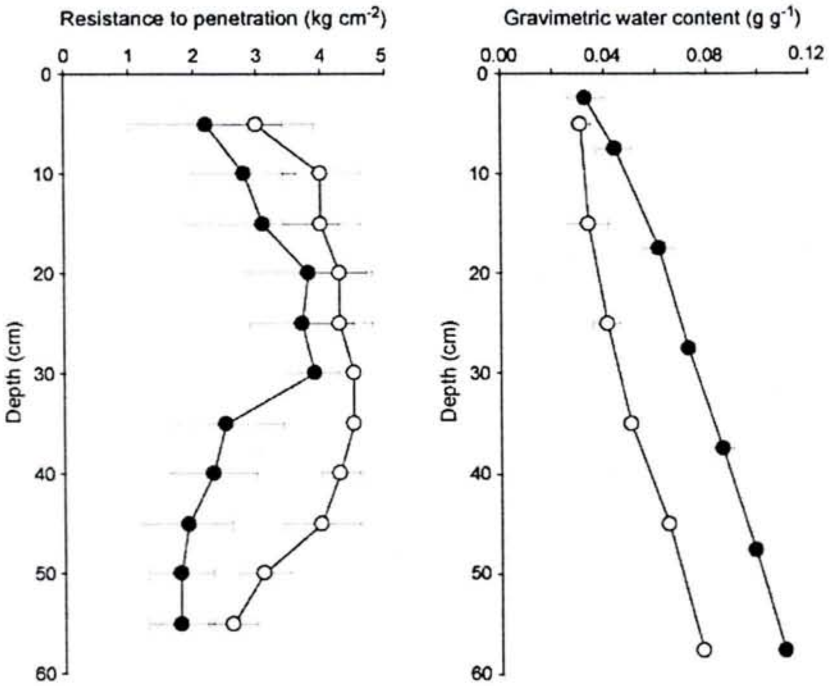

Figure 1: Resistance to penetration measured in the field with a pocket penetrometer. Both wet (-●-) and dry (-○-) conditions are presented with respective gravimetric water content profiles (average and standard deviation associated).

average of 2 plants per stand on ridge, as generally practised by farmers.

Five replications of CS and SM were destructively sampled to describe the stylo root system and macropore density after 24 and 4 months, respectively. The remaining 5 replicates for each treatment were used to describe these attributes at the end of the 3 year cycle. Macropore density of the compact layer was quantified in the field 2 weeks after harvesting stylo for both treatments.

In the final year of the study (year 3), maize (*Zea mays* cv. SW 3601) was grown using identical agronomic practices in the 10 remaining plots (SM=5; CS=5). Maize root systems were described for each treatment at the flowering growth stage. Total above-ground biomass, grain yield, cob number and weight were measured on each plot at physiological maturity.

Macropores quantification

Porosity is usually investigated through micromorphological observations of impregnated blocks or thin sections (Krebs *et al.*, 1994; Bruand *et al.*, 1996; Stewart *et al.*, 1999). These studies give accurate results but are time consuming and therefore not suited to large area observations. On the other hand, Volkmar (1996) observed that only macropores of equivalent diameter greater than 500 μm resulted in a positive correlation with root growth. As these macropores are visible to the naked eye, we estimated their density in the field using a similar methodology to that described by McKenzie and Jacquier (1997). Assuming that the main physical barrier to root proliferation occurs at 20-40 cm (Hartmann *et al.*, 1999), we limited our quantification of macropore to this layer.

The method used to quantify macropores consisted of initially excavating and removing the top 30 cm of the profile and then preparing a horizontal area (1 m^2) that is

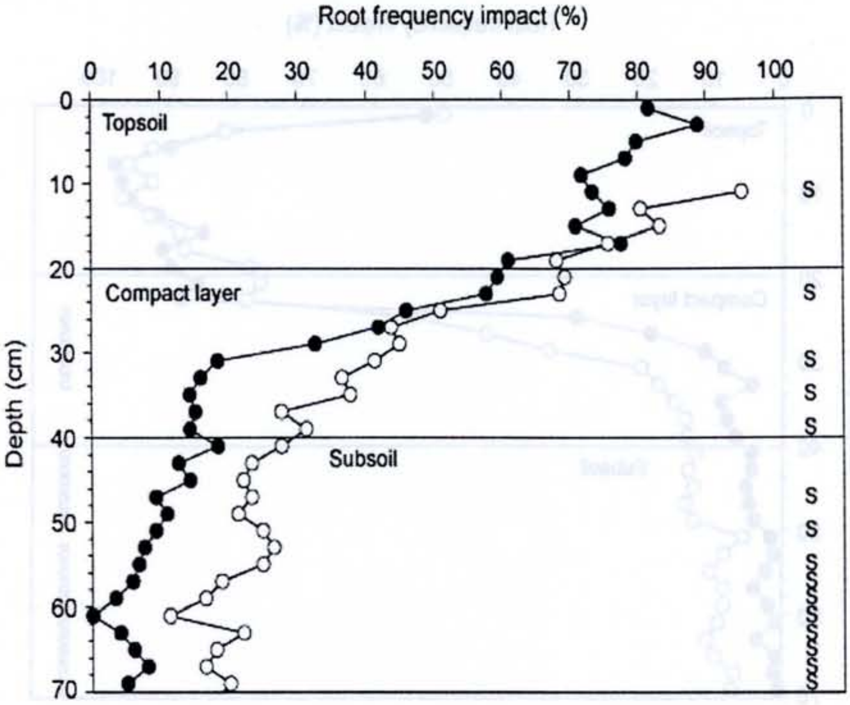

Figure 2: Root frequency impacts of *Stylosanthes hamata*, 4 months (–•–) and 24 months (–○–) after establishment. "S" indicates significant difference for the considered depth (n=5, P<0.05).

situated in the middle of the compact layer. When preparing a large and relatively flat soil surface in the field, it is often difficult to ensure that the structure and the porosity are not disturbed (i.e. by smearing of soil in some places). In our case, the structure of the soil is inherently unstable even after ploughing and subject to rapid slumping under wet conditions (Hartmann *et al.*, 2002). With respect to the compact layer (20-40 cm depth) that is below the ploughed layer and therefore unaffected by tillage operations, it has a massive structure and is therefore resistant to changes in structure and porosity due to disturbance (Bruand *et al.*, 2004). The structure of this layer is characterised by a close arrangement of fine sand that presents high resistance to deformation in the non-ploughed state. The clay, even though in small quantities, acts as a cementing agent under dry conditions, thereby increasing the soil strength and resistance to structural deformation when disturbed. Observations were made under dry conditions in order to limit any possible disturbance to the structure. The surface was carefully cleaned using a soft brush and air-blown in order to highlight macropores and decaying roots, and vertical macropores visible to the naked eye were quantified, independently of their shape or origin. Observations were undertaken on 5 plots per treatment with 25 replications per plot (125 macropore assessments for each treatment). There is no consensus on the definition of a macropore, especially on the range of equivalent diameter (Luxmoore *et al.*, 1990). In this study, we consider all pores of equivalent diameter > 500 µm as macropores.

Root system description

Tardieu (1988) concluded that the commonly used criteria of Lv (root length per unit of volume) and HMDR (half distance between neighbouring roots) are not adequate parameters for assessing root system structure in studies on the effects of soil tillage or compaction due to the horizontal variability of Lv. In

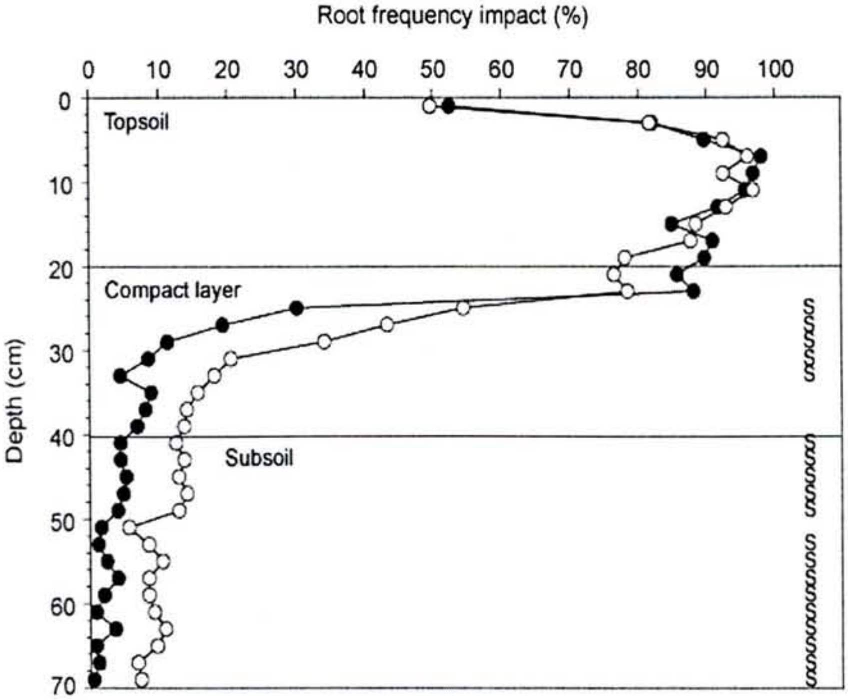

Figure 3: Root frequency impacts of a maize crop (in the third year of the study). Stylo/maize rotation (–•–) and continuous stylo treatment (–○–). "S" indicates significant difference for the considered depth (n=5, P<0.05).

order to characterize root systems as water and mineral element sinks, we used a mapping method, adapted from Tardieu and Manichon (1986), which consisted of mapping the frequency of roots on a 100×60 cm^2 vertical face (three plants for stylo, five for maize) using a 2×2 cm grid. A trench was dug perpendicular to the planting line for stylo and along the planting line for maize. Descriptions of the root distribution in each of the treatments consisted of determining the presence or absence of at least one root in each of the 2×2 cm cells for the entire exposed profile face. Using this approach, problems of root clumping due to the presence of cracks or holes is avoided. Results were expressed as root frequency impact (percentage of cells occupied by at least a root) for each depth (Tardieu and Manichon, 1986; Nicoullaud *et al.*, 1994).

Statistical analysis of all data was undertaken using the software package Statistix 7 (Analytical Software, 2000).

Results

Root frequencies of stylo

Figure 2 presents root frequencies of stylo after 4 and 24 months as a function of depth from the top of the ridge down to 70 cm. The height of the ridges changed with time due to their collapse and settling, and after 24 months, the original ridges were no longer evident. From 0 to 15 cm depth, roots were observed in approximately 80 % of the cells in both the 4 and 24 month samples. Whilst there was a decline in root frequency over this depth interval, regardless of sampling time, there were no significant differences between the CS and MS treatments. Conversely, over the 15-30 cm depth interval, frequency values decreased linearly with depth for both treatments (from 80 to 20-30 %). However, root frequencies were significantly (P<0.05) higher under the 24 month CS treatment when compared to the 4 month SM treatment and these differences persisted to 70 cm (Figure 2).

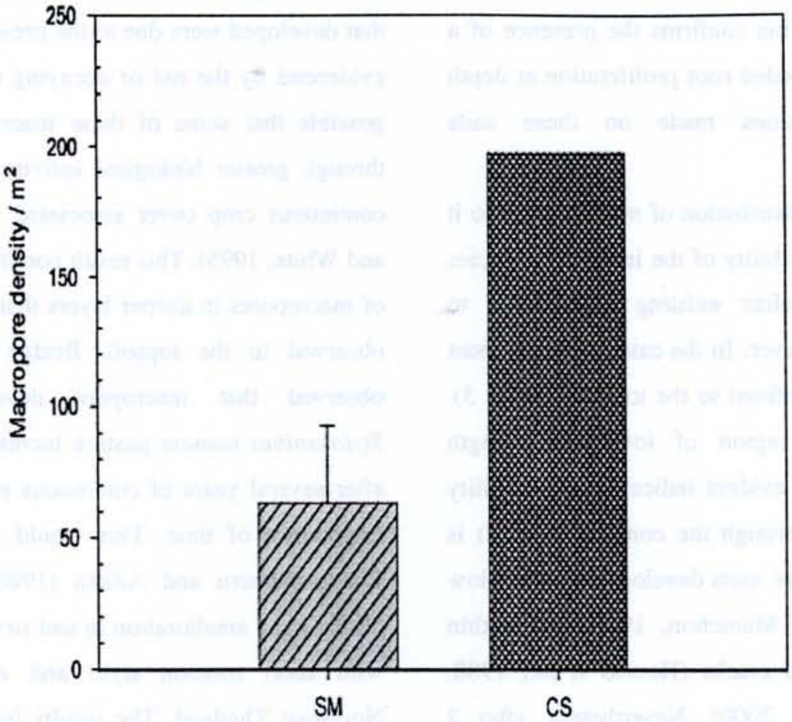

Figure 4: Vertically oriented macropore density of compact layer for the continuous stylo (CS) and stylo/maize rotation (SM) at 24 and 4 months respectively. Vertical bar is the Least Significant Difference between treatments at P=0.05 (LSD).

Root frequencies of maize

The root frequencies of the maize crop established in the third year of the study under the CS and SM treatments are presented in Figure 3. The shape of the frequency distribution curves was similar for both treatments with 80-90 % root frequency being recorded in the 0-10 cm depth interval with no significant differences between treatments. However, in the 10-70 cm depth interval, maize root frequencies were significantly ($P<0.05$) higher under the CS treatment when compared to SM treatment.

Macropore density in the compact layer

The presence of vertically-oriented macropores under the two treatments as a result of stylo production is presented for each treatment in Figure 4. Significantly ($P<0.05$) higher macropore densities were observed under the CS treatment when compared to the SM rotation treatment. Variability between individual replications of the same treatment was considerably higher under the SM treatments when compared with the CS treatment with coefficients of variation of 73 and 24 % respectively. Variability related to uncertainty of the method is difficult to estimate but considering that all replicates were processed under the same conditions, the variability is assumed to be the same for both treatments.

Discussion

Ability of stylo to develop roots in compacted soil layers

Regardless of species, root development and proliferation was greatest in the topsoil and ridge regions (Figure 2-3) where penetration resistance is lowest (Figure 1). However, root frequency rapidly declined when the compact layer was encountered. At depths below 40 cm, resistance to root growth decreased and therefore root frequency tended to remain constant with increasing depth. This confirms the presence of a physical barrier that impeded root proliferation at depth and previous observations made on these soils (Hartmann *et al.*, 1999).

By comparing the root distribution of maize and stylo it is possible to assess the ability of the individual species to either create or utilize existing macropores to overcome a compacted layer. In the case of maize, most of the root system is confined to the topsoil (Figure 3). However, below this region of low soil strength relatively few roots was evident indicating the inability of the species to pass through the compact layer. It is well recognized that maize roots develop in zones of low resistance (Tardieu and Manichon, 1987) and within existing macropores and cracks (Hatano *et al.*, 1988; McMahon and Christy, 2000). Nevertheless, after 2 years of continuous stylo, roots were able to penetrate this compacted layer, this being evidenced by the significantly higher root frequencies observed. This result supports previous observations made by Bajracharya *et al.* (1996) on the ability of stylo root systems to penetrate dense compacted layers. The fact that there is a significant increase in root frequencies between the 4 and 24 month would suggest that penetration of this layer does not occur during short rotations and that even stylo experiences difficulties in penetrating this layer in the short term. Under non-limiting physical conditions stylo roots have been observed to develop to significant depth (> 3 m) thereby allowing this species to actively grow during dry periods as is common to the semi-arid tropics (Williams and Probert, 1984).

Subsoil macropore creation by roots of stylo

Macropore density was observed to be significantly higher after continuous stylo when compared to the current advocated 4-month legume/crop rotation that is practiced by farmers in the region (Figure 4). This would suggest that the development of macropores within a compacted layer by stylo is time dependent. The assumption is made that most of the macropores that developed were due to the presence of stylo roots as evidenced by the old or decaying roots. However, it is possible that some of these macropores were created through greater biological activity associated with the continuous crop cover associated with stylo (Stirzaker and White, 1995). This result confirms the augmentation of macropores in deeper layers that Bridge *et al.* (1983) observed in the topsoil. Bridge *et al.* (1983) also observed that macropore development under a *Stylosanthes hamata* pasture increase significantly only after several years of continuous pasture indicating the importance of time. This would in part explain why Ruaysoongnern and Aitken (1980) were not able to observe any amelioration in soil structure in their studies with short rotation stylo and convention crops in Northeast Thailand. The results from the current study would suggest that in order to achieve structural amelioration of compacted layers on soil in Northeast Thailand using *Stylosanthes*, a minimum rotation of 2 years of continuous legume should be advocated.

The main advantage of macropores developed by roots when compared to subsoiling, is that they are stable and will persist. Characteristics of the compact layer on these sandy textured soils is that they have a massive structure, no aggregation and insufficient clay to allow structure maintenance through swelling/shrinking cycles. Mechanically modifying the structure of these resistant layers enhances porosity in the short term. However, due to the unstable nature of the structure of these soils the benefits of mechanical modification rapidly degenerates after a significant rainfall event as water acts as a lubricant thereby facilitating slumping (Hartmann *et al.*, 2002). In contrast, macropores developed from root channels are very stable because they develop in the stable structure of the compact subsoil and likewise the compaction exerted by the roots when growing within this layer makes them locally very coherent (Dexter, 1987; Bruand *et al.*, 1996).

Benefits to the subsequent maize root system

The root frequencies of maize were significantly higher in and under the compact layer after CS treatment (Figure 3). The structural improvement that continuous stylo induced in the compact layer benefited the rooting ability of the subsequent maize crop. Maize was able to develop a higher density of roots in the compact layer using macropores created by decaying roots of the previous stylo and also in the subsoil under this physical barrier where the resistance to penetration decreased (Figure 1). These results support the findings of Stirzaker and White (1995) and Stewart *et al.* (1999).

The fertility of sandy soils is inherently low and under high intensity rainfall regimes that are typical of most tropical climates this is exacerbated further through leaching of nutrients beyond the rooting depth of most plants. Therefore it is plausible that a plant with deep-rooting characteristics or one that would enhance rooting characteristics for the subsequent crop, represents a potential means of effecting better soil nutrient recycling and stored water utilization that is reflected in greater crop productivity (Salako *et al.*, 2002). In the present study there was no measured improvement in maize yield after continuous stylo. The lack of a significant response in the yield of maize could be attributed to the unusual growing conditions that prevailed towards the end of growing season, thereby masking any benefits associated with improved rooting. Successive heavy rainfall events resulted in the water table rising to near the surface during the critical flowering stage thereby preventing any water stress from occurring in the shallow-rooted MS treatments, whilst hydromorphic conditions may have affected the deep-rooted CS treatments. In addition, other confounding factors that are independent of soil structure may have affected the yield responses these including low soil pH (Noble *et al.*, 1997), microbial interactions and hormonal effect (Passioura, 1991). Shehu *et al.* (1997) showed in some cases, that intercropping maize with *Stylosanthes hamata* results in a reduction of maize yield when compared to pure stands of maize. Although they worked in a different cropping system (intercropping instead of rotation), where competition for water (Williams and Probert, 1984) and for nutrients (Haynes and Swift, 1984) are factors to take in consideration, they did not find any stylo beneficial effect on maize yield.

Conclusion

As a pasture species, *Stylosanthes hamata* is able to grow on degraded soils with low pH and is economically profitable as it provides forage for livestock. The advantages of stylo with respect to its ability to provide nitrogen to subsequent crops is well known and farmers of the Northeast routinely grow it in their crop rotations (Ruaysoongnern and Aitken, 1980).

This study demonstrated that *Stylosanthes hamata* is able to develop a significant quantity of roots both in and below a compact physical barrier and that is time dependent (e.g. at least 2 years under continuous stylo). Decaying roots of stylo create a large number of macropores that represent significant amelioration of the compact layer. Subsequent crops are able to take advantage of this amelioration through the development of a more extensive root system in and under the compact layer. This amelioration of compacted layers by roots represents a potential low cost means of improving crop productivity and face water stresses during dry spells.

The only way to grow crops on these degraded upland soils has long been to mechanically break the compact layer. However, due to the unstable nature of these soils they revert in less than one year to their original compact state through slumping during the rainy season with the corresponding collapse of macropores. By using stylo as a low-cost soil amelioration technique, the development of stable macropores can be achieved thereby enhancing the potential productivity of these soils. Further agronomic evaluations of the benefits associated with increased macroporosity through root drilling under adverse climatic conditions (i.e. water limiting conditions) is required. The potential effect of the structure amelioration on the yield should be investigated independent of the provision of nitrogen effects. Even if soil pH did not change significantly during the three years of the study, the risk of accelerated acidification (Noble *et al.*, 1997) should also be considered as a potential limiting factor with respect to promoting stylo on these soils.

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Annexe 8

Soil acidification without pH drop under intensive cropping systems in Northeast Thailand

Grégory Lesturgez, Roland Poss, Andrew Noble, Olivier Grünberger,
Woraphan Chintachao & Daniel Tessier

Acidification des sols sans baisse de pHdans les systèmes de culture intensifs du Nord-Est Thaïlandais.

L'objectif de ce travail était d'étudier l'acidification du sol induite par l'introduction de Stylosanthes hamata *(stylo) dans le système de culture d'une région tropicale semi-aride. La plupart des sols du Nord-Est Thaïlandais sont sableux et acides (pH 4.0 in* $CaCl_2$*) avec un fort drainage. L'acidification des sols a été étudiée à partir d'un essai en station expérimentale sur 6 ans, avec et sans apport de chaux. Les trois premières années, une rotation maïs-niébé a été comparée à un sol nu. Les trois années suivantes, une rotation mais-stylo a été comparée à une culture continue de stylo. L'acidification totale des sols a été calculée à partir des variations de pH et de l'effet tampon du sol. L'acidification due à l'activité du système racinaire a quant à elle été évaluée à partir des masses et alcalinités des cendres de la biomasse aérienne. Dans le système chaulé, le taux d'acidification du sol était élevé pour le sol nu (6.3 kmol* H^+ ha^{-1} yr^{-1}*) du fait du lessivage des engrais azotés. Les rotations maïs-niébé n'ont pas augmenté significativement ce taux (7.6 kmol* H^+ ha^{-1} yr^{-1}*), car les résidus de récolte ont été restitués sur la parcelle. L'introduction du stylo dans le système de culture a conduit à moins d'acidification lorsqu'il était cultivé en rotation avec le maïs (1.3 kmol* H^+ ha^{-1} yr^{-1}*) du fait d'un lessivage moindre. Par contre, la culture continue de stylo a déclenché une acidification accélérée (7.2 kmol* H^+ ha^{-1} yr^{-1}*) du fait des grosses quantités de biomasses alcalines exportées. Dans le système non chaulé, le pH est resté constant à pH 4.0 quel que soit le système de culture, et malgré que les générations acides aient été équivalentes à celle du système chaulé. Ce résultat prouve que le sol était fortement tamponné à pH 4.0. Les diagrammes de rayon-X montent que la kaolinite, argile dominante de ces sols, était plus désordonnée ou moins bien cristallisée dans les horizons de surface qu'en profondeur. Ceci suggère que la dissolution de la kaolinite est responsable de fort effet tampon des sols à pH 4.0.*

Soil acidification without pH drop under intensive cropping systems in Northeast Thailand

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Abstract

The aim of the study was to investigate soil acidification following the introduction of *Stylosanthes* in cropping systems of a tropical semi-arid region. Most soils in Northeast Thailand are sandy and acidic (pH 4.0 in $CaCl_2$), with high drainage rate. Soil acidification was studied in a six-year randomised block experiment with and without lime provision. In the first three years a rotation maize–cowpea was compared to a bare soil treatment. In the following three years, a rotation maize-*Stylosanthes* was compared to a continuous *Stylosanthes* treatment. Total soil acidification was calculated from pH change and pH buffer capacity. Acidification due to root system activity was evaluated from the weight of the above ground biomass and its ash alkalinity. In the limed systems, soil pH decrease was well correlated with ash alkalinity and crop removal. Acidification was high in the bare soil (6.3 kmol H^+ ha^{-1} yr^{-1}), due to leaching of applied N fertilizers. The cowpea-maize rotations did not increase significantly the rate (7.6 kmol H^+ ha^{-1} yr^{-1}), because crop residues were returned. The introduction of stylo in the cropping system resulted in less acidification when it was cultivated in rotations with maize (1.3 kmol H^+ ha^{-1} yr^{-1}), because of lower leaching rate. In contrast, continuous cultivation of Stylosanthes triggered an accelerated acidification (7.2 kmol H^+ ha^{-1} yr^{-1}), because of the large quantities of biomass high in ash alkalinity removed. In the no-lime system, pH kept stable at pH 4.0 whatever the cropping system, even though the acid generating processes were quite similar to those in the limed treatments. This result proves that the soil was strongly buffered at pH 4.0. XRD diagrams showed that kaolinite, the main clay mineral, was more disordered and less crystalline in the surface horizons than at depth. It is suggested that the dissolution of kaolinite is responsible for the buffering of soil pH at 4.0.

Introduction

Light textured sandy soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975; Panichapong, 1988). Such soils occupy a large area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). The vegetation of the region was originally dominated by climax *Dipterocarp* forests until

40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils are productive in that they support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne *et al.*, 1998). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC < 2 $cmol_c\ kg^{-1}$) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999).

Soil acidification is a naturally occurring phenomenon and is usually the result of long-term additions of protons to the upper layers of the soil profile that effectively results in the displacement of exchangeable bases and their subsequent leaching. However, accelerated acidification of soils associated with increases in the losses of products of acid reactions in the biological carbon and nitrogen cycles has brought into question the long-term sustainability of these production systems (Helyar, 1976; Helyar *et al.*, 1990).

Stylo *(Stylosanthes sp.)* is a legume commonly grown in Northeast Thailand for forage production. Continuous cultivation of this legume proved to be an efficient and low cost method to ameliorate soil structure (McCallum *et al.*, 2004), especially for compact layers of sandy soil (Lesturgez *et al.*, 2004). However, the risk of accelerated degradation due to acid generation by stylo based production systems over a range of agroecozones has been highlighted (Noble *et al.*, 1997; Liu Guodao *et al.*, 1999). Like temperate legume species, stylo fixes nitrogen and increases the N status of the soils (Ruaysoongnern and Aitken, 1980; Thomas *et al.*, 1997; Oikeh *et al.*, 1998). In this respect, Jones *et al.* (1991) demonstrated that appreciable amounts of N are fixed in a stylo-based system in the semi-arid tropics of northern Australia and that significant leaching of nitrate occurs, creating the potential for accelerated acidification. Moreover, the physiological constitution of legumes induces a net efflux of protons at the root-soil interface that is significantly higher than that observed under non-nitrogen fixing species such as the *gramineae* (Tang *et al.*, 1998; Tang *et al.*, 1999). In addition, when the forage produced is removed from the field to feed animals, massive losses of alkalinity stored in the biomass of stylo occurs. The consequence of a combination of these three factors in Northeast Thailand, is accelerated soil acidification following the introduction of a stylo-based production system, that is a major concern for the sustainability of stylo-based cropping systems (Noble *et al.*, 2001).

The objective of this study was to ascertain whether accelerated soil acidification occurred through the incorporation of stylo into cropping systems, and the consequences of a decline in soil pH on clay mineralogy.

Material and methods

Site characteristics and soils

The study was conducted over a six-year period in Northeast Thailand at the Land Development Department research station located 15 km from Nakhon Ratchasima, Korat province (15°N, 102°E). Northeast Thailand is characterised by a semi-arid tropical climate with a distinct rainy season from April to October and a dry season from November to March. The mean annual rainfall for Nakhon Ratchasima is 1020 mm. Annual and monthly rainfall is highly variable on a year to year basis (minimum = 599 mm and maximum = 1446 mm for the period 1971-1998). Rainfall generally exceeds evaporation during the growing season and at least 3 months of the year there is no precipitation. The soil at the experimental site is a sandy texture and belongs to the *Nam Phong* soil series (Imsamut and Boonsompoppan, 1999). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) and Arenic Acrisol (FAO classification). Selected chemical and physical characteristics of the soil are presented in Table 1.

Experimental design

A completely randomised block design with 5 replications containing the treatment combinations presented in Table 2 and Table 3 were established prior to the commencement of the cropping season in 1996. Each plot had an initial area of 48 m^2 to which either no lime (L_0) or lime (L_1) was applied as $Ca(OH)_2$ to raise the soil pH_{Ca} to 5.0 (measured in 0.01 M $CaCl_2$) and incorporated into the 0-20 cm depth interval using a rotor tiller. L_1 received lime twice, 650 kg ha^{-1} in 1996 to raise the initial soil pH_{Ca} to 5.0 and 850 kg ha^{-1} in 1998 in order to maintain this value (Figure 1).

Each treatment (L_0 and L_1) were subsequently divided in half and sub-treatments M or F applied. There were therefore a total of 4 treatments imposed (Table 2).

Crop husbandry

Crop husbandry commonly conducted by farmers was adapted with the addition of applying adequate levels of nutrition to avoid possible deficiencies. 20 kg N ha^{-1} was applied each year to the legume crop as KNO_3 and urea. In the first year the legume received 50 kg ha^{-1} of P and 56 kg ha^{-1} of K as triple super phosphate and KNO_3 respectively. In the following years the same fertilizers were applied at the rate of 10 kg ha^{-1} of P and 30 kg ha^{-1} of K. The corn received between 100 and 150 kg ha^{-1} of N as KNO_3 and urea in 4 applications. In the first year the corn received 50 kg ha^{-1} of P and 112 kg ha^{-1} of K as triple super phosphate and KNO_3. During the following years the same fertilizers were applied at the rate of 20 kg ha^{-1} of P and 60 kg ha^{-1} of K. Mg, Zn and S were applied each year as $MgSO_4$ and $ZnSO_4$ to prevent any deficiency. Fertilizers were applied at the same level in cultivated as well as bare plots (1996-1999) in order to avoid any effect of fertilizer application in comparisons.

Plant biomass and alkalinity

For maize and cowpea the grain was harvested and plant residues were left on the plots as commonly undertaken by farmers. Contrasting this, the entire above ground biomass was removed from the plots after stylo had been harvested in order to reach the maximum rate of acidification and to simulate a cut-and-carry production system often undertaken by farmers. For the legumes (cowpea and stylo) the biomass was determined on 20 plants per plot one month after sowing and at harvest. In the case of the maize, biomass was determined on 10 plants per plot three weeks after sowing, at flowering stage and at harvest. The ash alkalinity was determined on all plant samples using the methodology of Jarvis and Robson (1983).

Sampling and pH measurements

Soil samples were collected on several occasions (beginning of experiment, after lime application, at the end of the bare fallow phase and at the conclusion of the study) during the intervening 6-year period. Samples were collected at 10 cm intervals to a depth of 100 cm from six points within each plot using a hand auger, with a composite sample being produced for each depth

Table 1: Selected soil physical and chemical properties of the Arenic Acrisol at the study site.

Depth (cm)	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in μm*								OC (%)	CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1000	1000-2000	2000-5000			Mean	SD
10-15 cm	37	63	60	381	357	81	19	2	0.19	0.9	1.48	0.07
25-35 cm	53	64	61	399	331	75	17	<1	0.17	1.2	1.69	0.05
40-50 cm	88	65	69	347	324	96	11	<1	0.08	2.3	1.67	0.05

OC is organic carbon content, CEC is cation-exchange capacity, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n=5).

interval. Samples were air-dried and sieved to pass a 2 mm mesh before pH was measured in both water (pH_w) and 0.01 M $CaCl_2$ (pH_{Ca}) using 1:5 soil:solution. For brevity only the results from pH_{Ca} are discussed as pH measured in a dilute salt solution reduces seasonal effects due to variations in soil solution salt concentrations due to the application of fertilizers. Estimation of pH buffer capacity (pH_{BC}) was undertaken using the methodology of Aitken and Moody (1994) on composite samples from each depth interval on samples collected at the start of the study and at the end. A mean value ($5.2\ 10^{-6}$ kmol $H^+.kg^{-1}.pH\ unit^{-1}$) was calculated and used in the determination of the net acid addition rate (NAAR).

Estimation of the proton balance

The proton balance was assessed using two complementary methods, i) the changes in soil pH (Net Acid Addition Rate), and ii) alkaline exportations from the plot (Acid Generation).

Changes in soil pH are linked to the proton balance by the following equation (Helyar and Porter, 1989):

$$NAAR = (pH_i - pH_f) \times pH_{BC} \times BD \times V / T \quad (1)$$

where the subscript i and f refer to initial and final pH respective value; pH_{BC} is the mean pH buffering capacity (kmol $H^+\ kg^{-1}\ pH\ unit^{-1}$) of the considered soil. BD is the bulk density (expressed in kg m^{-3}); V is the soil volume in the depth interval under consideration ($m^3\ ha^{-1}$) and T is the duration of the considered period (years). This estimation of proton addition is based on the fact that pH_{BC} is usually constant between pH 4 and pH 7. This equation effectively encapsulates all mechanisms that contribute to soil acidification, as long as acidic composts are not used (Helyar and Porter, 1989). The net acid addition rate was estimated from the sum of all depth intervals where there was a significant ($P<0.05$) difference in pH_{Ca} between the two times of measurement. The effective NAAR was calculated from NAAR by taking into account lime addition over the considered period (kmol $OH^-\ ha^{-1}\ yr^{-1}$).

Measurement of ash alkalinity on plant biomass samples, effectively represents the influence of the root system on the net efflux of proton into the soil (i.e. the excretion of protons or hydroxyl ions in order to maintain the electro neutrality within the plant). Acid

Table 2: Treatments and cropping sequences.

Treatment	Description
L_0M	No lime applied; first 3 years rotation of maize-mungbean and maize-black cowpea; 3 years maize-stylo rotation.
L_1M	1.5 t ha lime applied to increase soil pH_{Ca} to 5.0; first 3 years rotation of maize-mungbean and maize-black cowpea; 3 years maize-stylo rotation.
L_0F	No lime applied; first 3 years bare fallow; next 3 years continuous stylo.
L_1F	1.5 t ha lime applied to increase soil pH_{Ca} to 5.0; first 3 years bare fallow; next 3 years continuous stylo.

Table 3: Cropping pattern over the 1996-2001 period.

Treatment	Year					
	1996	1997	1998	1999	2000	2001
M	Mungbean-Maize	Cowpea-Maize	Cowpea-Maize	Stylo-Maize	Stylo-Maize	Stylo-Maize
F	Bare fallow	Bare Fallow	Bare Fallow	Continuous Stylo	Continuous Stylo	Continuous Stylo

generation (AG) (kmol H^+ ha^{-1} yr^{-1}) associated with crop export was calculated using the biomass (grains and plant residues) removed from the plot (kg ha^{-1}) and its respective ash alkalinity (cmol H^+ kg^{-1}). T is the duration of the considered period (years):

$$AG = \Sigma(\text{Biomass exported} \times \text{Ash alkalinity}) / T \quad (2)$$

The acid addition generated by leaching was estimated by difference between the effective NAAR (total proton addition) and AG (proton addition by root excretion).

Mineralogy

Soil samples were collected at the end of the study from three adjacent plots kept bare throughout the study period in order to avoid any treatment interactions. Samples were collected at five depths (10, 30, 50, 70 and 90 cm) using a hand auger. Composite samples were produced for each depth. Clay fractions (<2-µm) were obtained by centrifugation from the initial samples after organic matter oxidation (H_2O_2-treated clay). Mineralogical analysis was performed by X-ray diffraction on powder samples obtained by grinding <2-mm air-dried soil and on oriented samples obtained by sedimentation of the <2-µm fractions on glass slide and air-drying. The XRD's of powder samples, air-dried Mg-saturated and K-saturated, heated at 520°C <2-µm were produced using a Philips PW3020 diffraction system with CoKα radiation. The patterns were decomposed into elementary curves using the program DECOMPXR (Lanson, 1997) in order to measure precisely the intensity, width and area of the peaks.

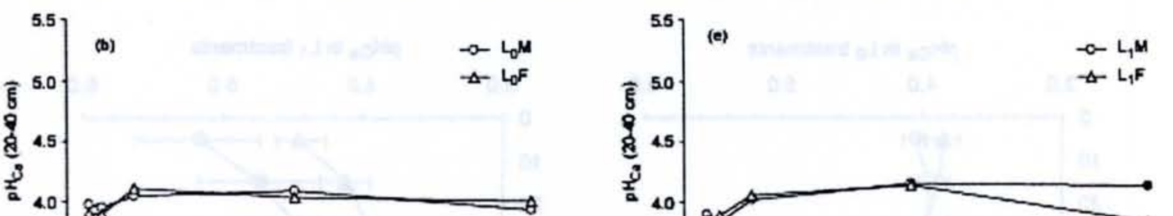

Figure 1: Change in pHCa at three depths (0-20, 20-40 and 40-60 cm) over the entire study period. The mean of five replications are presented for each sub-treatments M (–○–) and F (–Δ–) for both L0 (no-lime) and L1 (lime) treatments. Filled symbols correspond to statistically significant differences between the M and F (P<0.05).

Results

pH monitoring

An overview of changes in pH_{Ca} at different depth intervals down the soil profile over the entire study period is presented in Figure 1. At the initiation of the study the mean pH_{Ca} over all depth intervals (0-60 cm) and treatments was 3.87±0.01, clearly indicating the uniform reactivity of these soils to depth (Figure 1). In those treatments receiving no lime (L_0) additions, pH_{Ca} did not change significantly over the duration of the study regardless of the cropping system imposed (Figure 1 a, b, c). Contrasting this, those treatments receiving an initial application of lime (L_1) in 1996 resulted in a significant increase in pH_{Ca}. This increase was greatest in the 0-20 cm depth interval with the pH_{Ca} increasing from 3.94±0.03 to 4.99±0.29 within 2 months of the initial application of lime (Figure 1 d, e, f). The influence of lime additions was predominantly confined to the surface 0-20 cm with little or no significant impact below this layer. Significant differences between cropping treatments (F and M) were observed with depth on samples collected at the conclusion of the study (Figure 1 d, e, f). The pH_{Ca} of those treatments under a continuous stylo (F) cropping regime were significantly lower than those under a continuous legume/maize (M) rotation. These differences in pH_{Ca} were significant to a depth of 60 cm (Figure 1 d, e, f).

The pH_{Ca} profiles for each of the treatments at the conclusion of the study in 2002 are presented in Figure 2. No significant differences in pH_{Ca} between treatments L_0M and L_0F were observed below 10 cm (Figure 2 a). The pH_{Ca} under the stylo (F) treatment was significantly lower in the 0-10 cm compared to the legume/maize (M) rotation (Figure 2 a). It is of note that the mean pH_{Ca} below the 0-10 cm remained relatively constant at 3.86±0.02 and did not vary from the initial pH_{Ca} of 3.87±0.01 recorded at the start of the study suggesting that no net acid addition had occurred of the intervening period regardless of cropping system. In those treatments receiving lime (L_1), pH_{Ca} was significantly higher ($P<0.05$) in treatments L_1M than in L_1F over the 0-60 cm depth interval (Figure 2 b).

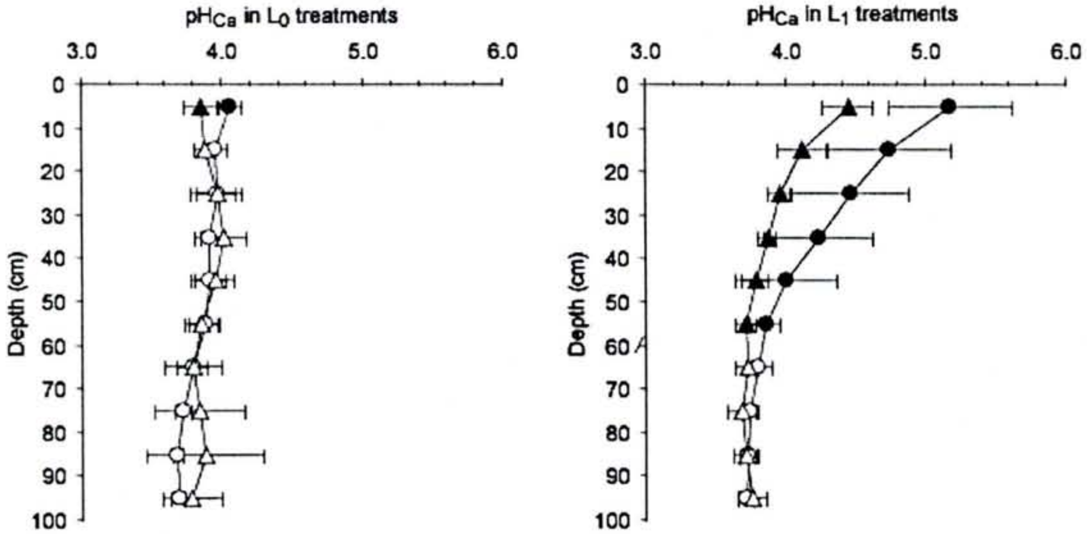

Figure 2: Soil pH_{Ca} profiles for each treatment at the end of the experiment. Mean and confidence interval ($P<0.05$) on five plots are presented for each sub-treatment M (–○–) and F (–Δ–) both in L_0 (no-lime) and L_1 (lime) treatments. Filled points correspond to statistically significant differences between the two means ($P<0.05$).

Table 4: Ash alkalinity, yield components and annual acid generation due to crop removal under different liming regimes and cropping sequences for the period 1996-2001.

	Grain			Above-ground biomass (without grain)			Acid generation due to crop export
	Ash alkalinity	Yield	Acid generation	Ash alkalinity	Dry matter production	Acid generation	
	cmol OH^- kg^{-1}	kg ha^{-1}	kmol H^+ ha^{-1} yr^{-1}	cmol OH^- kg^{-1}	kg ha^{-1}	kmol H^+ ha^{-1} yr^{-1}	kmol H^+ ha^{-1} yr^{-1}
Cowpea-Maize (1996-1998) in L_0M							
Cowpea	35	572	0.2	164	971	1.6*	0.2
Maize	24	1210	0.3	38	3156	1.2*	0.3
Cowpea-Maize (1996-1998) in L_1M							
Cowpea	34	800	0.3	171	1518	2.6*	0.3
Maize	27	1321	0.4	45	3878	1.8*	0.4
Stylo-Maize (1999-2001) in L_0M							
Stylo	-	-	-	120	218	0.3	0.3
Maize	15	923	0.1	41	3762	1.5*	0.1
Stylo-Maize (1999-2001) in L_1M							
Stylo	-	-	-	120	115	0.1	0.1
Maize	15	1990	0.3	41	4354	1.8*	0.3
Continuous Stylo (1999-2001)							
L_0F	-	-	-	105	5391	5.6	5.6
L_1F	-	-	-	108	6125	6.6	6.6

* biomass of cowpea and maize retained on the plots and therefore not included in the determination of the net acid addition rate due to crop export.

Table 5: Proton budget associated with soil pH changes and estimated acid generation from crop removal for the different cropping systems where lime had been applied.

Period	Cropping system	Lime	NAAR [1]	eff. NAAR[2]	AG [3]	Leach. [4]
		(kmol OH^- ha^{-1} yr^{-1})	(kmol H^+ ha^{-1} yr^{-1})			
L_1M (1996-1998)	Cowpea-Maize rotations	13.5	-5.9	7.6	0.7	6.9
L_1F (1996-1998)	Bare	13.5	-7.2	6.3	-	6.3
L_1M (1999-2001)	Stylo-Maize rotations	-	1.3	1.3	0.4	0.9
L_1F (1999-2001)	Continuous Stylo	-	7.2	7.2	6.6	0.6

[1] Net Acid Addition Rate is calculated using Equation (1).
[2] Effective Net Acid Addition Rate = Lime + NAAR
[3] Acid Generation calculated from Equation (2).
[4] Acidification induced by leaching = eff. NAAR - AG.

Alkalinity export and acidification rate

The mean ash alkalinity values associated with the grain export, total crop vegetative biomass and the net acid generation due to crop export are presented Table 4. The annual net acid addition rates associated with grain export under the legume/maize (M) rotational cropping system was low (< 0.5 kmol H^+ ha^{-1} yr^{-1}) this being due to the retention of cowpea and maize stubble on the plots. In addition, the amount of acid generated by the export of stylo in a crop rotational (M) systems was also low (< 0.3 kmol H^+ ha^{-1} yr^{-1}) this being due to the very low biomass production (115-218 kg ha^{-1}) in these systems (Table 4). In contrast, the net acid addition rate associated with the export of forage (between 5391-6125 kg ha^{-1}) under the continuous stylo (F) for the period 1999-2001 ranged between 5.6-6.6 kmol H^+ ha^{-1} yr^{-1} (Table 4).

Mineralogy of the soil

XRD patterns for the whole soil (<2-mm fraction) is presented in Figure 3 for the 0-10 cm depth interval only, as the other depth intervals gave similar results. The XRD clearly indicates the dominance of quartz (peaks at 4.25 and 3.34 Å). However, the XRD patterns of the <2-µm fractions (Figure 4) showed the presence of quartz, kaolinite and also 2:1 minerals at 14.5 Å in minor proportions (Figure 4). The presence of kaolinite is confirmed by comparing the XRD patterns of K and Mg saturated samples as the peaks at 7.37 Å and 3.57 Å disappeared upon heating to 520°C.

Table 6 presents characteristics of the three main peaks: quartz (4.27 Å), kaolinite (7.37 Å) and 2:1 clay mineral (14.64 Å). The surface area of the quartz peak relative to the total surface area decreased with depth, indicating that the proportion of alumino-silicate (kaolinite and 2:1 minerals) increased with depth. The proportion of 2:1 minerals, although relatively minor when compared to other constituents, was highest in the 0-10 cm depth interval.

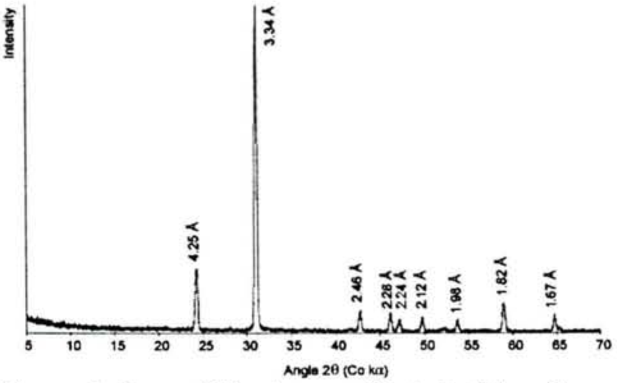

Figure 3: X-ray diffractogram (Co kα) of the <2 mm soil fraction collected from the 10 cm depth interval for the control treatment.

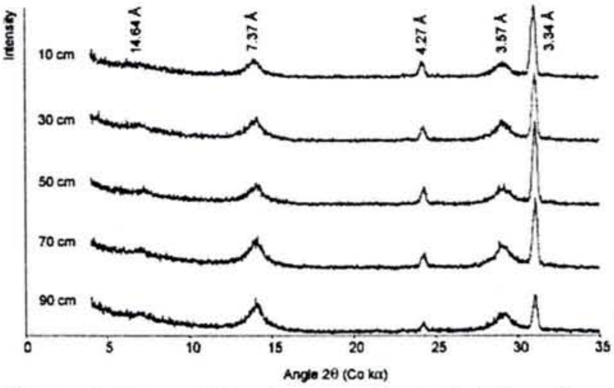

Figure 4: X-ray diffractograms (Co kα) of the <2-µm fraction for each sample depth interval for the control treatment.

Discussion

Lime application and soil pH

The initial application of lime to treatments L_1 in 1996 increased the pH_{Ca} in the 0-20 cm depth interval by 1.1 units in both the L_1M and L_1F plots 2 months after incorporation (Figure 1 d). The effect of this initial application on pH_{Ca} was confined to the layer of incorporation and was not affected by the cropping pattern (M and F) at this point (Figure 1). The increase in soil pH associated with the application of lime was equivalent to the neutralisation of 16.2 kmol H^+ ha^{-1}. This value is slightly lower but consistent with the theoretical value of 17.6 kmol OH^- ha^{-1} calculated for 650 kg ha^{-1} of pure $Ca(OH)_2$, given that acidification occurred between lime application and soil sampling. A second application of lime to L_1 treatments was undertaken in 1998. However, when plots were sampled 1 year after this second application there was no evidence of an increase in soil pH when compared to the previously measured value (Table 1). The high acidification rate between 1996 and 1998 (7.6 kmol H^+ ha^{-1} yr^{-1}) can explain why no direct relationship was observed between soil pH and lime application.

Influence of leaching on soil acidification

In L_1M, the acidification rate was 7.6 kmol H^+ ha^{-1} yr^{-1} during the 1996-1998 period (Table 5). As the acid generation by crop removal was equivalent to 0.7 kmol H^+ ha^{-1} yr^{-1}, acidification induced by leaching was estimated to be 6.9 kmol H^+ ha^{-1} yr^{-1} (Table 5). Similarly, on the L_1F treatment the rate of acidification associated with leaching losses was calculated to be 6.3 kmol H^+ ha^{-1} yr^{-1}, as there was no crop component since the plots were kept clean of vegetation (Table 5).

These results highlight the importance of leaching on soil acidification in these semi-arid climates with a distinct wet season. The absolute value associated with acidification due to leaching is probably an over-estimation, as it is assumed that all OH^- derived from lime were consumed in the neutralization of protons, and that the lime was pure. Even assuming a slight overestimation of the net acid contribution due to leaching, this value exceeds the quantity of acid generated by an export of biomass, if all biomass was removed from the plot (Table 4). This high acidification rate is probably due to the leaching of nitrate from fertilizers (120 kg N ha^{-1} $year^{-1}$), leaching of nitrate produced by the mineralization of the crop residues from the previous year, and leaching of bicarbonate. Under such a climatic regime, cowpea-maize rotations did not increase significantly the bare soil acidification rate, already high, as acid generation induced by crop removal is very low compared to the leaching component.

Continuous stylo and soil acidification

Stylo was introduced into the cropping sequence in 1999. Rotations of stylo-maize and continuous stylo cultivation were imposed respectively to M and F treatments. In the L_1M treatment, pH_{Ca} remained constant in the 0-40 cm depth interval and declined by 0.2 units in the 40-60 cm layer over the 3-year period (Figure 1), corresponding to a net acidification rate of 1.3 kmol H^+ ha^{-1} $year^{-1}$ for the 0-60 cm interval (Table 5). This value is consistent with the estimation of acid addition calculated from product removal, which did not exceed 0.4 kmol H^+ ha^{-1} $year^{-1}$ for stylo-maize rotation, leading to an acidification rate due to leaching of 0.9 kmol H^+ ha^{-1} $year^{-1}$.

In L_1F treatment, pH_{Ca} declined by 0.7 and 0.3 units respectively in the 0-20 cm and 20-60 cm depth intervals

Table 6: Surface areas, intensity, width at middle height (FWHM) and disorder indices obtained from modelling of the tree main peaks.

Depth (cm)	Surface areas of the 3 main peaks (%)			Kaolinite peak at 7.37 Å		
	14.64 Å 2:1 clay minerals	7.37 Å Kaolinite	4.27 Å Quartz	Intensity	FWHM	DI*
10	16	62	21	48	1.118	$2.33\ 10^{-2}$
30	17	70	14	61	1.048	$1.72\ 10^{-2}$
50	14	67	19	58	1.042	$1.80\ 10^{-2}$
70	13	73	14	75	1.153	$1.54\ 10^{-2}$
90	8	85	7	97	1.091	$1.12\ 10^{-2}$

* Disorder Indice is the ratio between FWHM and the intensity of the peak

over the same period (Figure 1), corresponding to a net acidification rate of 7.2 kmol H^+ ha^{-1} $year^{-1}$ for the 0-60 cm interval. This net acidification rate is also consistent with the estimation of acid addition calculated from product removal, which increased net acid input associated with biomass export to 6.6 kmol H^+ ha^{-1} $year^{-1}$ (Table 5). By difference, the acidification rate due to leaching was 0.6 kmol H^+ ha^{-1} $year^{-1}$.

The leaching components determined for the period 1999-2001 under the two cropping regimes were both very low compared to those calculated for the same treatments over the 1996-1998 period (Table 5). The two factors to explain this result are the low level of fertilizer application on stylo and the deep rooting system of stylo in this soil type (Lesturgez *et al.*, 2004).

Stylo in rotation with maize resulted in a moderate rate of acidification (1.3 kmol H^+ ha^{-1} $year^{-1}$). This result is largely associated with the low level of biomass produced by stylo when grown for as an annual crop and the fact that the biomass of maize was retained on the plot (Table 5). Contrasting this, under the highly exploitive monoculture stylos production system (F), the measured acidification rate of 7.2 kmol H^+ ha^{-1} $year^{-1}$ is of the same order of magnitude (10 kmol H^+ ha^{-1} $year^{-1}$) as estimated for a stylos seed production system in Northern Australia (Noble *et al.*, 1997).

Existence of a threshold value

Comparison between L_0 and L_1 treatments highlights the existence of a minimum value of pH_{Ca} (approximately 4.0 in $CaCl_2$) below which pH appears to be buffered, thereby introducing methodological limitations in accessing acidification rate using pH changes. Over the entire study period, pH_{Ca} did not change significantly on treatment L_0 regardless of the cropping system imposed (stylo-maize rotation or continuous cultivation of stylo). This suggests that net acid addition rate estimated from soil pH and pH_{BC} is not an appropriate method for assessing acidification under the prevailing circumstances.

Over the period 1996-1998, treatments L_0F and L_1F were not cropped and hence the acidification resulted only from leaching. Assuming that the leaching rates were similar in both sets of treatments over this period, one would predict that the acidification rates would be same. However, the pH drop and the corresponding acidification rate measured on L_1F were not observed in the L_0F treatment suggesting no net acid addition (Figure 1).

Similarly in the cropped system, the acid generated by crop removal and leaching induced a pH drop in L_1M treatment but not in L_0M (Figure 1). Acid generation by crop removal was lower in L_0 treatment as the lime had an effect on yield and ash alkalinity of crop residue, but values presented in Table 4 highlights the lack of response in pH_{Ca} value to the acid input generated by crops. In the cropped system with high acidification rate as continuous cultivation of stylo, it became obvious that pH had reached a threshold value and that acid generated by the plants was strongly buffered (Figure 2). In the soil under study, the buffer capacity was very high at pH_{Ca} 4.0 and acidification took place without pH drop, independently of the acidification generated by the crop. The calculations proposed by Helyar and Porter (1989) or Noble *et al.* (1997) are assumed to be effective in assessing soil acidification as they include all acidification processes in simple measurements. However, in the current study where there is no evidence of a pH decline, the appropriateness of previously used methods to estimate NAAR is brought into question. The only way to estimate the acidification rate in such a buffered system is therefore to quantify acid generation by crop removal and leaching of nitrate and bicarbonate.

Origin of the threshold value of soil pH

The stable minimum value of soil pH_{Ca} of approximately 4 is consistent with survey data generated during frequent mapping exercises of Northeast Thailand soils (Haimsrichat *et al.*, 1993). Most soils appear indeed to have a soil surface pH around this value, or slightly higher. This suggests that pH_{BC} increases considerably as soil pH_{Ca} approaches 4. As soil organic matter is low in these soil the most likely reason to explain the lack of pH decline is the dissolution of secondary minerals, as these soils do not contain primary minerals (Figure 3).

The XRD patterns of the <2-µm fraction indicated that the soil consists of kaolinite, small quartz grain and traces of 2:1 clay mineral (Figure 4). The kaolinite appears disordered, as the first peak is much larger and displaced (7.37 Å) compared to a well ordered kaolinite (Brindley, 1980). This disorder can be attributed to various properties of the mineral: small size of the crystal; poor crystallinity (Hughes and Brown, 1979); and mixed layer kaolinite (Yoothong *et al.*, 1997). These properties can be inherited from the parental material, as well as a result of weathering of soil minerals. However, the presence of disorder in kaolinite is consistent with the hypothesis of kaolinite dissolution (Brindley, 1980).

The surface areas of the peaks (Table 6), measured after modelling of the patterns (Lanson, 1997), gives a semi-quantitative assessment of each of the constituents (Pernes-Debuyser, 2003). The quartz content was high and the ratio kaolinite/quartz increased with depth. These results are consistent with the measurements of Bruand *et al.* (2004) on the same site, who observed also a high proportion of quartz in the <2-µm fraction of the soil, ranging from 25.3 in the surface to 34.5 % at 60 cm depth. The relative increase of kaolinite in the <2-µm fraction at depth suggests a migration to the lower layers or dissolution of kaolinite in the upper layers. The relationship between intensity (maximum height of peak) and the width at half maximum intensity (FWHM) of the first kaolinite peak (7.37 Å) is a basic indicator of the disorder of the mineral (Brindley, 1980). Using this relation it appeared that there is a greater quantity of disordered kaolinite in the surface horizon and therefore crystallinity of kaolinite increases with depth (Table 6). This is consistent with the hypothesis of clay dissolution associated with net acid addition is more intense in the surface layers of the profile.

It is suggested that when these soils reach the threshold value of 4.0, the dissolution of kaolinite becomes the main buffering mechanism. This is consistent with the pH (4.0) at which the dissolution of kaolinite naturally occurs (Sposito, 1994). In addition, it is suggested that the lack of highly ordered kaolinite throughout the profile is evidence of the degraded state that these soils have attained. It is plausible that changed land use has accelerated these processes.

Using the stoichiometric Equation (3) and assuming that all of the protons added are buffered by the dissolution of kaolinite and there are no limiting factors, an addition of 6 kmol H^+ ha^{-1} $year^{-1}$ would induce the dissolution of approximately 250 kg of kaolinite ha^{-1} $year^{-1}$.

$$Al_2Si_2O_5(OH)_4 + 6\,H^+ \leftrightarrow 2\,Al^{3+} + 2\,H_4SiO_4 + H_2O \quad (3)$$

This value is small when compared with the kaolinite content of the soil (around 412 Mg ha^{-1} in the 0-60 cm depth interval). However, the corresponding release of aluminium, which is toxic for crops (Calba *et al.*, 2004), and silica, which could act in the cementation of the soil (Bruand *et al.*, 2004), may have a significant impact on soil processes.

Conclusion

The main objective of the study was to estimate the risk of accelerated soil acidification following the incorporation of stylo into cropping systems. Soil pH response to similar acid additions was different depending on the initial soil pH, and therefore the monitoring of soil pH in limed and no-limed system highlighted different processes.

In the limed system, where pH_{Ca} was above 4.0 in $CaCl_2$, cropping systems induced a significant soil pH drop, well correlated to alkaline exportation. The acidification rate of bare soil due to leaching was high and cowpea-maize rotations did not significantly increase the rate, as alkaline exportations were low. The introduction of stylo in the cropping system did not result in an accelerated acidification when it was cultivated in rotations as a starter crop. However, the long term and continuous cultivation of the same crop, with the objective of improving soil porosity, significantly increased the acidification rate.

In no-limed systems, ash alkalinity and crop removal were similar as in the limed systems, but pH_{Ca} remained stable around 4.0 independent of the cropping system imposed. This result suggests a threshold value under which protons are consumed without a corresponding decline in pH. Kaolinite, which can be dissolved in this pH range is probably a key factor in this equilibrium. The disorder in the kaolinite layers observed in the XRD traces and the lack of other minerals susceptible to be weathering, are consistent with this hypothesis.

Beyond the methodological limits in determining acidification rate using simple pH changes, the problem of sustainability and management of such system where acidification goes unnoticed but may have an impact on mineralogical degradation of the soil resource is highlighted in this study. Further studies focusing on clay mineralogy are needed to investigate the role and kinetics of kaolinite dissolution in soil pH buffering. Such weathering would not significantly affect the quantity of clay minerals in the short- to medium-term, but consequences are to find in aluminium toxicity and re-precipitation of silica involved in cementation processes.

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Densification des sols sableux sous culture mécanisée. Cas du Nord-Est Thaïlandais.
G. Lesturgez, 2005. Thèse de l'Université Henri-Poincaré Nancy (France), 164 pp.

La thèse aborde le cas des sols sableux du Nord-Est Thaïlandais. La présence à faible profondeur d'un horizon dense et résistant est une contrainte majeure pour l'agriculture. Trois volets sont traités : (i) analyse de l'état physique de ces sols dans différentes situations sous végétation naturelle et sous culture, (ii) identification des principaux mécanismes à l'origine des différents états physiques enregistrés et (iii) recherche de méthodes de réhabilitation des sols dégradés. Les résultats montrent que ces sols proviennent de dépôts éoliens. Ce mode de transport leur confère une grande homogénéité texturale et des propriétés mécaniques particulières. Ils sont très sensibles au tassement et s'effondrent à de faibles teneurs en eau et sous de faibles contraintes mécaniques. Les labours conventionnels sont à proscrire en raison de l'instabilité structurale qu'ils induisent. En revanche, des techniques alternatives telles que le rainurage ou la bio-perforation y sont efficaces.

Mots clefs : Sols sableux, Propriétés physiques, Tassement, Thaïlande, Rainurage, Bio-perforation, Exoscopie des quartz, Acidification.

Densification of sandy soils under mechanised agriculture. Case of Northeast Thailand.
G. Lesturgez, 2005. Thesis University Henri-Poincaré Nancy (France), 164 pp.

The thesis focuses on sandy soils of Northeast Thailand. A compact and resistant layer developed at low depth is a main constraint for agriculture. The thesis follows a sequence of studies that investigates (i) the physical properties of these soils in various situation natural or cultivated, (ii) the main mechanisms explaining the different physical states recorded and (iii) the research of methods for rehabilitation of damaged soils. Results highlighted the aeolian origin of the soils. This origin gives them a striking textural homogeneity and unique mechanical characteristics. Very sensitive to compaction, they collapse at low water content and under low mechanical pressure. Conventional tillage practices are not suitable as they induce structural instability. However alternative techniques as slotting or biological drilling are efficient.

Keywords : Sandy soil, physical properties, Compaction, Thailand, Slotting, Bio-perforation, Quartz microtextures, Acidification.