

Apport du silicium dans les cultures de céréales: les verrous scientifiques

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The Use of Si-Based Fertilization to Improve Agricultural Performance

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-> Un total de 467 articles jusqu'en 2021 a été sélectionné, aboutissant à 682 cas où différents engrais à base de silicium (Si) ont été utilisés.

Abstract

Silicon (Si) is a “quasi-essential” element, associated to stresses/limitations alleviation in crops. However, stressful situations are becoming the norm, due to climate change, human exhaustion of natural resources, land degradation and loss of soil biodiversity. In this context, Si becomes a critical element, capacitating crops to grow more and better with less. A total of 467 articles up to 2021 were selected, reporting 501 experiments (lab-oriented and field trials) resulting in 682 cases where dif

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-> Les résultats montrent que 63 % des cas testant la fertilisation au silicium (Si) présentent une augmentation de la productivité, tandis que 13 % ont infirmé cette observation et 24 % n'ont pas évalué la croissance des plantes

5% and only 14% reported yield loss. Si fertilization is therefore an important factor to improve crop yield and capacitate crops with resilience to endure future limitations. Its inclusion in modern agriculture should be considered in larger scales to adapt crops to the current challenges of sustainable agriculture and food provision.

-> Si bénéfique pour le prélèvement et la translocation des éléments essentiels

TABLE 1 | Evidence for Si-mediated expression of genes encoding transporters for essential and beneficial elements in plants.

Conditions	Plant species	Localization/direction/form/function	Transporter genes	Expression pattern by Si	References
Low N	Rapeseed	Root/influx/nitrate/uptake	<i>BnNRT1.1</i> , <i>BnNRT2.1</i>	Up-regulated	Haddad et al., 2018
High N	Rice	Root/influx/ammonium/uptake	<i>OsAMT1;1</i>	Down-regulated	Wu et al., 2017
		Root/influx/nitrate/uptake	<i>OsNTR1.1</i>		
Low P	Wheat	Root/influx/phosphate/uptake	<i>TaPHT1;1</i> , <i>TaPHT1;2</i>	Up-regulated	Kostic et al., 2017
High P	Rice	Root/influx/phosphate/uptake	<i>OsPHT1;6</i>	Down-regulated	Hu et al., 2018
Low K	Sorghum	Root cortex/influx/K ⁺ /xylem unloading	<i>SbHAK5</i> , <i>SbAKT1</i>	Down-regulated	Chen et al., 2016b
		Root cortex/efflux/K ⁺ /xylem loading	<i>SbSKOR1</i> , <i>SbSKOR2</i>	Up-regulated	
Low S	Rice	Root/influx/sulfate/uptake	<i>OsSULTR1;1</i> <i>OsSULTR1;2</i> <i>OsSULTR2;1</i> <i>OsSULTR2;2</i>	Down-regulated (up to 3 d of S deficiency) Down-regulated Down-regulated (from 1 to 3 d of S deficiency) Down-regulated (15 d of S deficiency)	Réthoré et al., 2020
Low Fe	Cucumber	Root/influx/Fe ²⁺ /uptake	<i>CsIRT1</i>	Up-regulated (3 d of Si supply)	Pavlovic et al., 2013
		Leaf/efflux/Fe(II)-complex/phloem mobilization	<i>CsYSL1</i>	Up-regulated	Pavlovic et al., 2016
	Barley	Root/influx/Fe(III)-complex/uptake	<i>HvYS1</i>	Up-regulated (5 h of Si supply)	Nikolic et al., 2019
High Mn	Rice	Root/influx/Mn ²⁺ /uptake	<i>OsNramp5</i>	Down-regulated	Che et al., 2016
High Cu	Arabidopsis	Root/influx/Cu ²⁺ /uptake	<i>AtCOPT1</i> , <i>AthHMA5</i>	Down-regulated	Li J. et al., 2008
	Rice	Root/influx/metal ions/translocation	<i>OsHMA2</i>	Down-regulated	Kim et al., 2014
		Root/efflux/metal ions/sequestration	<i>OsHMA3</i>	Down-regulated	
	Tobacco	Root/influx/Cu ²⁺ /uptake	<i>NtCOPT1</i>	Down-regulated	Flora et al., 2019
High Zn	Rice	Root/influx/Zn ²⁺ /uptake	<i>OsZIP1</i>	Down-regulated	Huang and Ma, 2020
High B	Barley	Leaf/efflux/H ₃ BO ₃ /export out of symplast	<i>HvBOR2</i>	Up-regulated	Akcaay and Erkan, 2016
High Na	Maize	Root/efflux/Na ⁺ /export and xylem loading	<i>ZmSOS1</i> , <i>ZmSOS2</i>	Up-regulated	Bosnic et al., 2018
		Root/influx/Na ⁺ /uptake	<i>ZmHKT1</i>	Down-regulated	
		Leaf/influx/Na ⁺ /vacuolar sequestration	<i>ZmNHX</i>	Up-regulated	

Pavlovic J, Kostic L, Bosnic P, Kirkby EA and Nikolic M (2021) Interactions of Silicon With Essential and Beneficial Elements in Plants. *Front. Plant Sci.* 12:697592. doi: 10.3389/fpls.2021.697592

-> Prélèvement active de Si chez les plantes accumulatrices ($\geq 1\%$ MS)

Plant Physiology and Biochemistry 165 (2021) 173–186

Table 4

List of silicon transporters reported in cereal crops.

Crop	Si transporter	Type	Reference
Rice	<i>Lsi1</i>	Channel type	Ma et al. (2006)
Rice	<i>Lsi2</i>	Efflux type	Ma et al. (2007a)
Rice	<i>Lsi3</i>	Efflux type	Yamaji et al. (2015)
Rice	<i>Lsi6</i>	Channel type	Yamaji and Ma (2009)
Wheat	<i>TaLsi1</i>	Channel type	Montpetit et al. (2012)
Barley	<i>HvLsi1</i>	Channel type	Chiba et al. (2009)
Barley	<i>HvLsi6</i>	Channel type	Yamaji et al. (2012)
Barley	<i>HvLsi2</i>	Efflux type	Mitani et al. (2009a)
Maize	<i>ZmLsi1</i>	Channel type	Mitani et al. (2009b)
Maize	<i>ZmLsi6</i>	Channel type	Mitani et al. (2009b)
Maize	<i>ZmLsi2</i>	Efflux type	Mitani et al. (2009a)

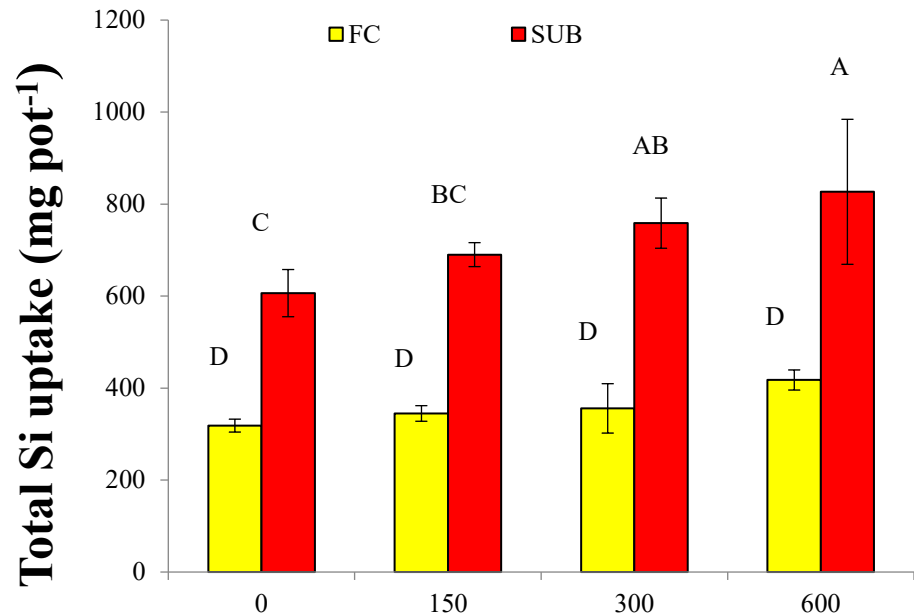
Engrais à base de Si:

- Laitiers/scories issus de produits de l'industrie (« slags »): silicates de calcium /magnésium (total Si = 15-25%) qui peuvent contenir des traces de métaux lourds: appliqués au Japon, en Chine**
- Produits manufacturés: 1-silicate de potassium et de magnésium (résultat de fusion, 12-14 % Si); fabriqués et appliqués en Chine; 2- gel de silice; 3- solution de silicate de sodium ou de potassium**
- Produits naturels: 1-mines de wollastonite (CaSiO_3) de diatomites (silice amorphe de test de diatomées); 2- produits riches en phytolithes: pailles, biochar**

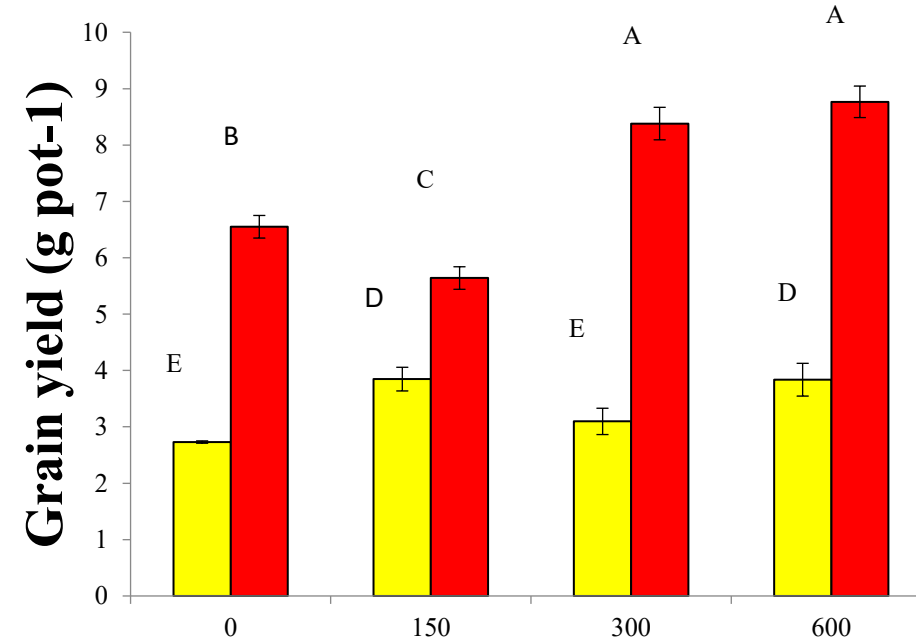


Si facteur limitant en rizière inondée, sols acides

Pot experiment: soils from Karnataka; rice; with Recommended Dose of Fertilizers (RDF) , $\pm$ Australian DE (CEFIPRA project 5109-1, Kollalu et al, 2018, JSSPN); Sandy clay loam, pH= 4.48



Kg/ha



The effect of DE in acidic soils

- At FC: no increase of Si uptake and only a slight yield increase
- At Sub: low pH=>increase of Si uptake from DE and an increase of grain yield

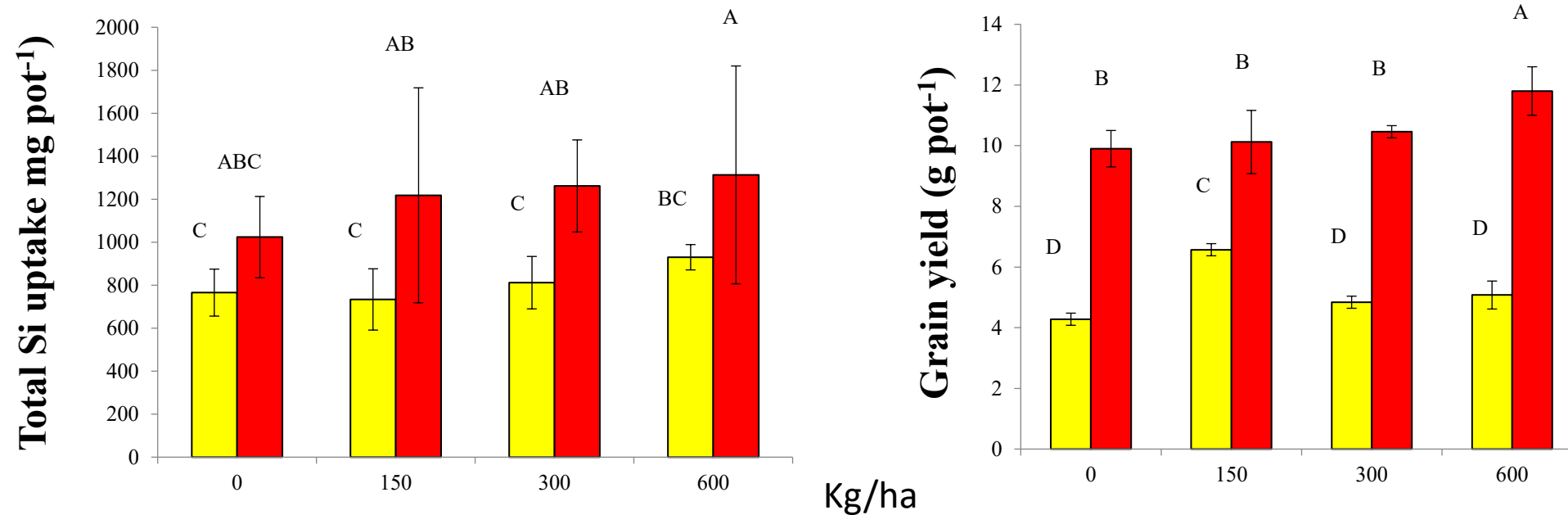
Sandhya et al, 2018, JSSPN



Si non limitant sur sols neutres

Sandhya et al, 2018, JSSPN

Pot experiment: soils in Karnataka, rice, RDF, $\pm$ Australian DE
(CEFIPRA project 5109-1 Kollalu et al, 2018, JSSPN) Sandy clay loam, pH 6.51



The effect of DE in near-neutral soils

- At FC: no increase of Si uptake and only a slight yield increase at 150 kg/ha
- At Sub: no Si uptake increase but a slight yield effect at the highest dose of DE

Table 6
Correlation between plant-available Si as extracted by different
extractants and yield parameters

No.	Extractants	Straw yield	Grain yield	Straw Si	Grain Si	Straw Si uptake	Grain Si uptake	Total Si uptake
1	0.5 M acetic acid 1	0.44	0.70**	0.76**	0.52*	0.75**	0.72**	0.80**
2	0.5 M acetic acid 2	0.47*	0.75**	0.82**	0.54*	0.80**	0.74**	0.83**
3	0.5 M acetic acid 3	0.20	0.45	0.63**	0.23	0.51*	0.41	0.51*
4	0.01 M CaCl ₂	0.39	0.68**	0.74**	0.58*	0.68**	0.65**	0.75**
5	Distilled water 1	0.34	0.68**	0.75**	0.54*	0.71**	0.69**	0.75**
6	Distilled water 4	0.36	0.67**	0.73**	0.45	0.70**	0.64**	0.72**
7	0.5 M NH ₄ OAc	0.33	0.69**	0.82**	0.48*	0.70**	0.68**	0.74**
8	N NaOAc-1	0.49*	0.78**	0.85**	0.56*	0.82**	0.75**	0.84**
9	N NaOAc-2	0.47*	0.72**	0.81**	0.53*	0.78**	0.73**	0.81**
10	0.1 M Citric acid	0.22	0.56*	0.77**	0.49*	0.56*	0.68**	0.64**
11	0.005 M H ₂ SO ₄	0.32	0.61**	0.72**	0.27	0.67**	0.52*	0.65**

**, * Significant at 1% and 5% respectively.

Narayanaswamy and Prakash (2010)

**Verrou
scientifique 1:
meilleure
connaissance
de la fraction
biodisponible
de Si**

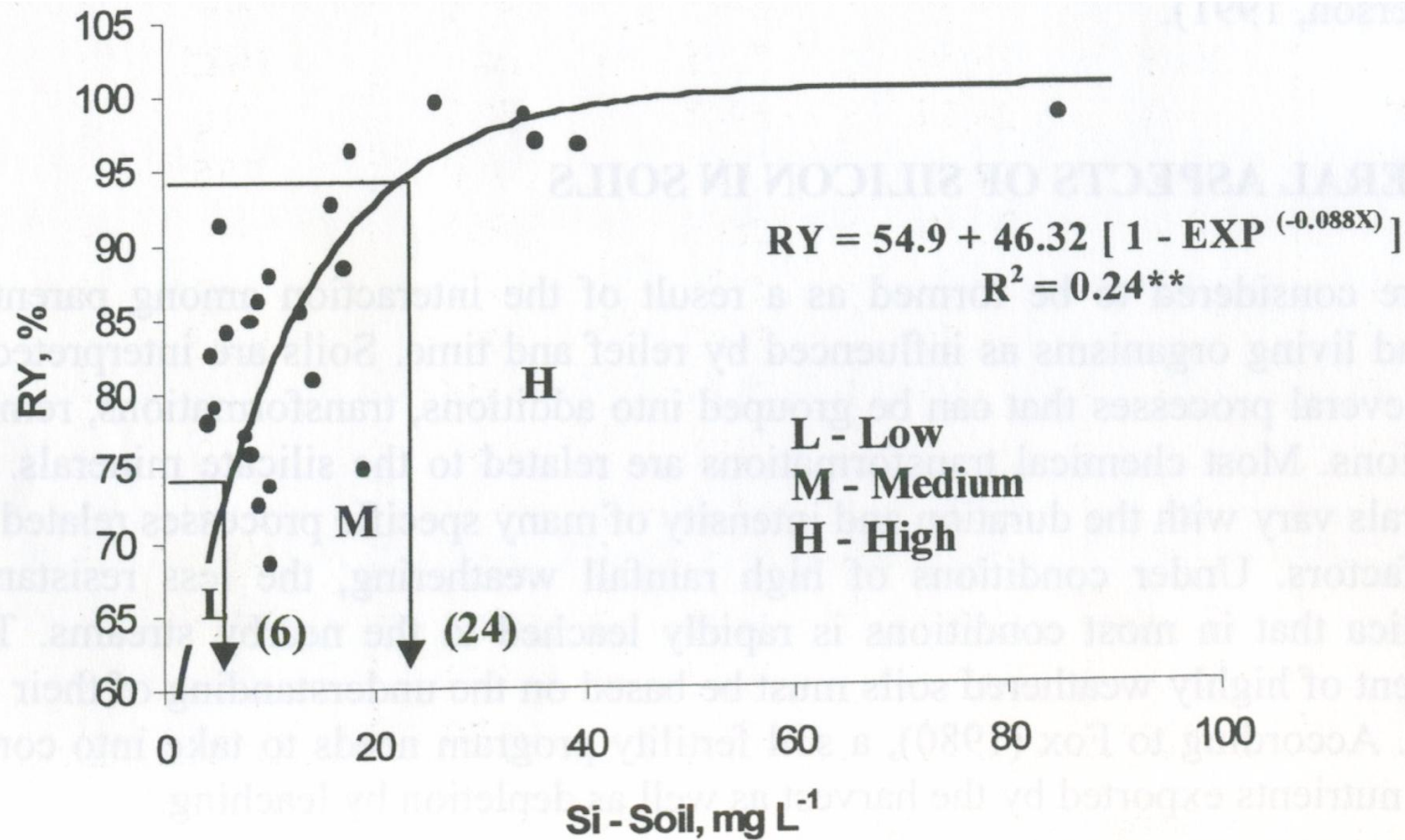


Figure 7.1. Calibration of soil test Si to relative yield (RY) for rice grown in the EAA, Histosol.

(Korndörfer and Lepsch, 2001, Datnoff et al., eds)

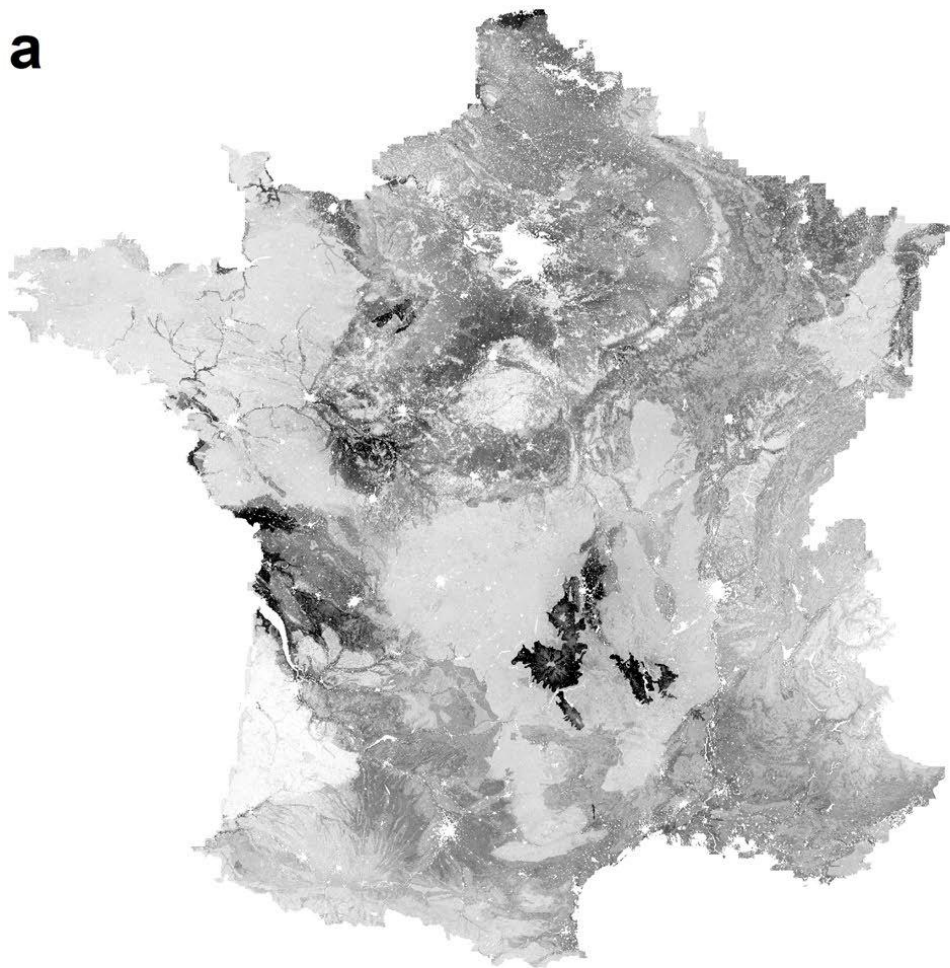


nécessité d'apport de Si au sol pour < H/M (critical level)

**A partir des extracteurs-> valeurs critiques = en dessous->
Si devient limitant -> nécessité d'appliqué des fertilisants Si**

Extractant	type de sols	Plante	Valeur critique (mg Si/Kg)	Référence
H2O	acide (ultisol)	riz	14	Narayanaswamy and Prakash, 2009
0,01 M CaCl ₂	acide (ultisol)	riz	43	Narayanaswamy and Prakash, 2009 Haysom and Chapman, 1975 Babu et al. (2016)
	acide	canne à sucre	20	
	Acide (alfisol, inceptisols)	rice	37-43	
0,5M acide acétique	histosol	riz	19	Snyder, 1991 Narayanaswamy and Prakash, 2009
	acide (ultisol)	riz	54	
Na acétate-acide acétique	calcaire	blé	80	Xu et al., 2001

a



Si_{CaCl2} (mg kg⁻¹)

Max: 95



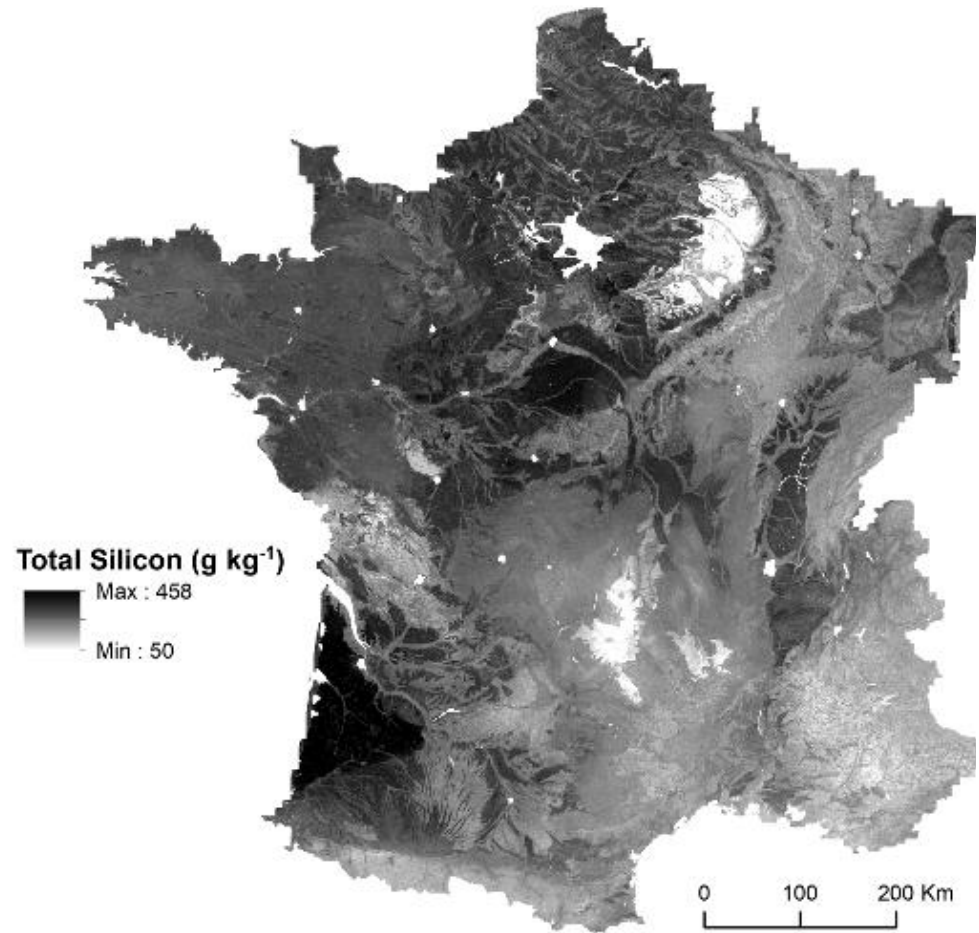
Min : 2.0

**2011 sites du Réseau de
Mesures de la Qualité
des Sols (RMQS)**

Caubet,
Cornu,
Saby,
Meunier
(2020,
Scientific
Reports
projet ANR
BIOSiSOL)



**Faut-il utiliser des engrais à
base de Si dans les cultures
céréalières en France?**



Total Silicon (g kg⁻¹)

Max : 458

Min : 50

Landré,
Cornu,
Meunier,
Guerin,
Arrouays,
Caubet,
Ratié, Saby
(2020,
Geoderma,
projet ANR
BIOSiSOL)

Corrélation de Pearson entre Si_{CaCl2} et Si_{total} = - 0,32 *
(p-value<0.0001; n= 1986)**

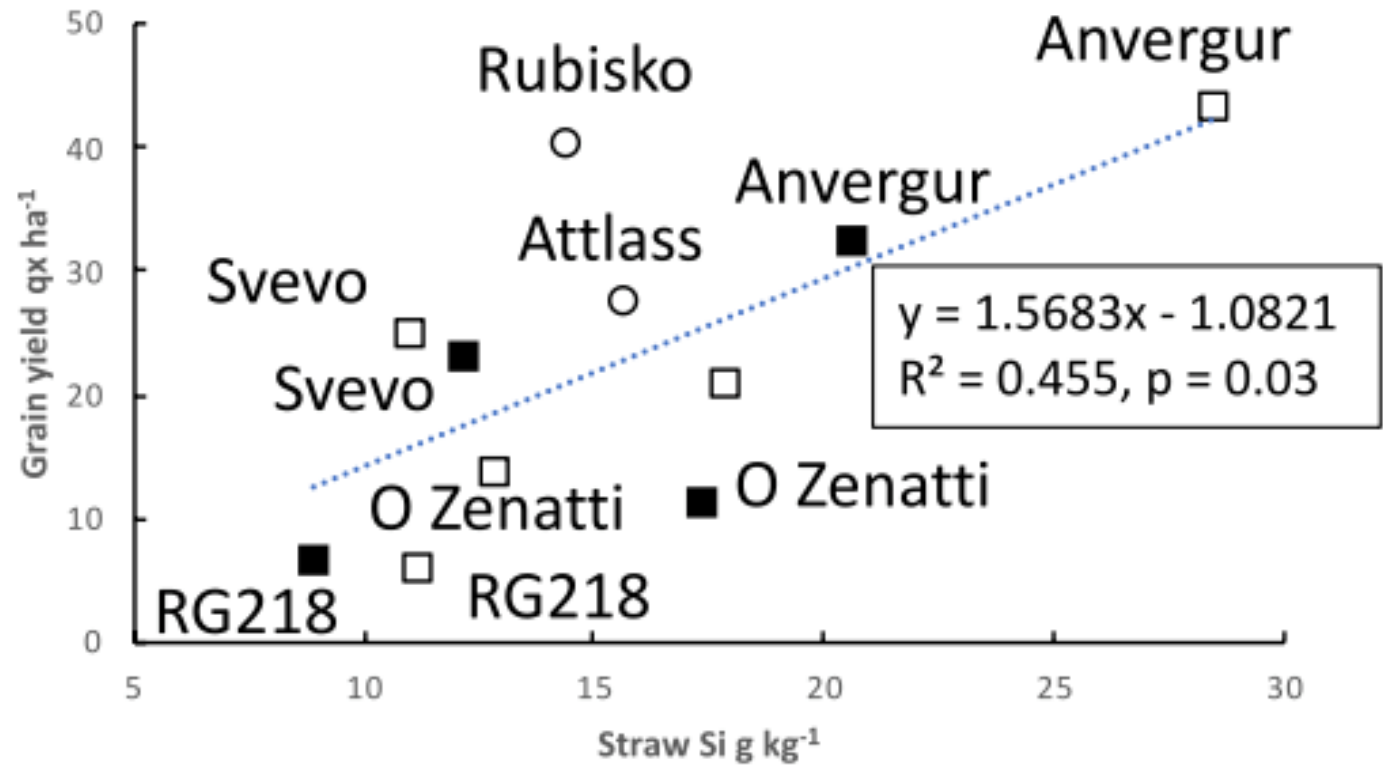
Class	Si _{CaCl2} ~ pH	Si _{CaCl2} ~ (< 2 µm fraction)	Si _{CaCl2} ~ (< 2 µm CEC)	n
All non-cultivated soils	0.46	0.59	0.44	1065
Carbonated soils on sediment	– 0.099	0.2	0.093	219
Soils on igneous extrusive rock	0.63	0.66	0.63	27
Soils on igneous intrusive rock	0.25	0.39	0.36	109
Soils on metamorphic rock	0.3	0.42	0.3	120
Non-carbonated soils on sediment	0.48	0.68	0.48	537
Podzols	0.034	0.81	0.15	53

2011 sites du Réseau de Mesures de la Qualité des Sols (RMQS)

Caubet, Cornu, Saby, Meunier (2020, Scientific Reports projet ANR BIOSiSOL)

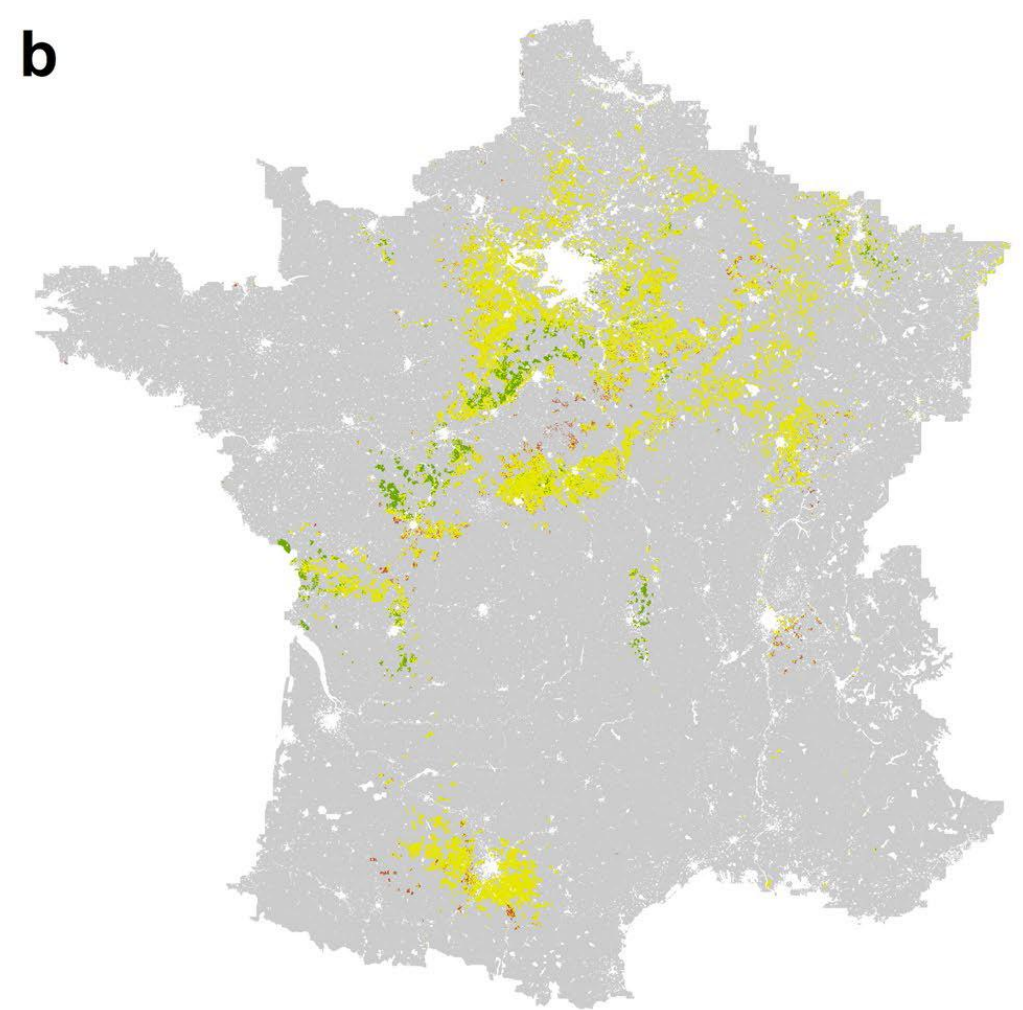
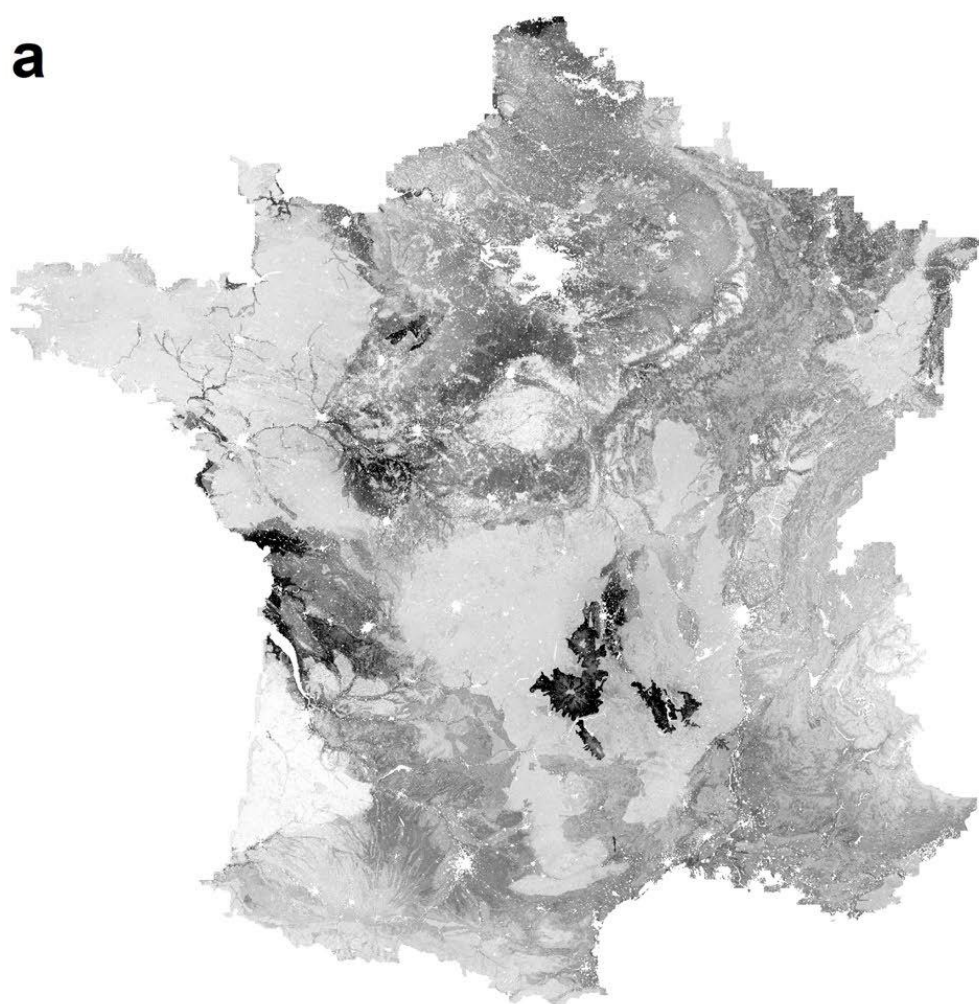
Verrou 2: vers une meilleure connaissance des besoins en céréales autres que le riz dans les pays tropicaux

Fig. 1 Correlation between Si straw and grain yield for the 10 wheat samples (Table 3) grown at the Mauguio station; circles: *Triticum aestivum*; squares: *Triticum turgidum*; in white: conventional treatment (CON); in black: control (CTR)



Des essais sur le terrain ont été menés à la station expérimentale INRAE de Mauguio (UE DiaScope), près de Montpellier, dans le sud de la France

**-20 mg kg⁻¹, le
seuil critique
établi pour la
canne à sucre
en Australie
(Haysom et
Chapman,
1975)**
**-40 mg kg⁻¹, le
seuil critique
établi pour le
riz en Louisiane
et en Inde
(Babu et al,
2016;
Narayanaswam
y and Prakash,
2009)**



SiCaCl₂ (mg kg⁻¹)

Max: 95



Min : 2.0

 < 20

 20 - 40

 > 40



Mask of non cultivated land + non principal wheat-producing regions

Caubet, Cornu, Saby, Meunier
(2020, projet ANR BIOSiSOL)

0

250

500 Km



Review article
Terrestrial and aquatic ecosystems

Advancing our understanding of the dynamics of silicon at the soil-plant scale since Bartoli's work (1980s)

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E-mail: meunier@cerege.fr

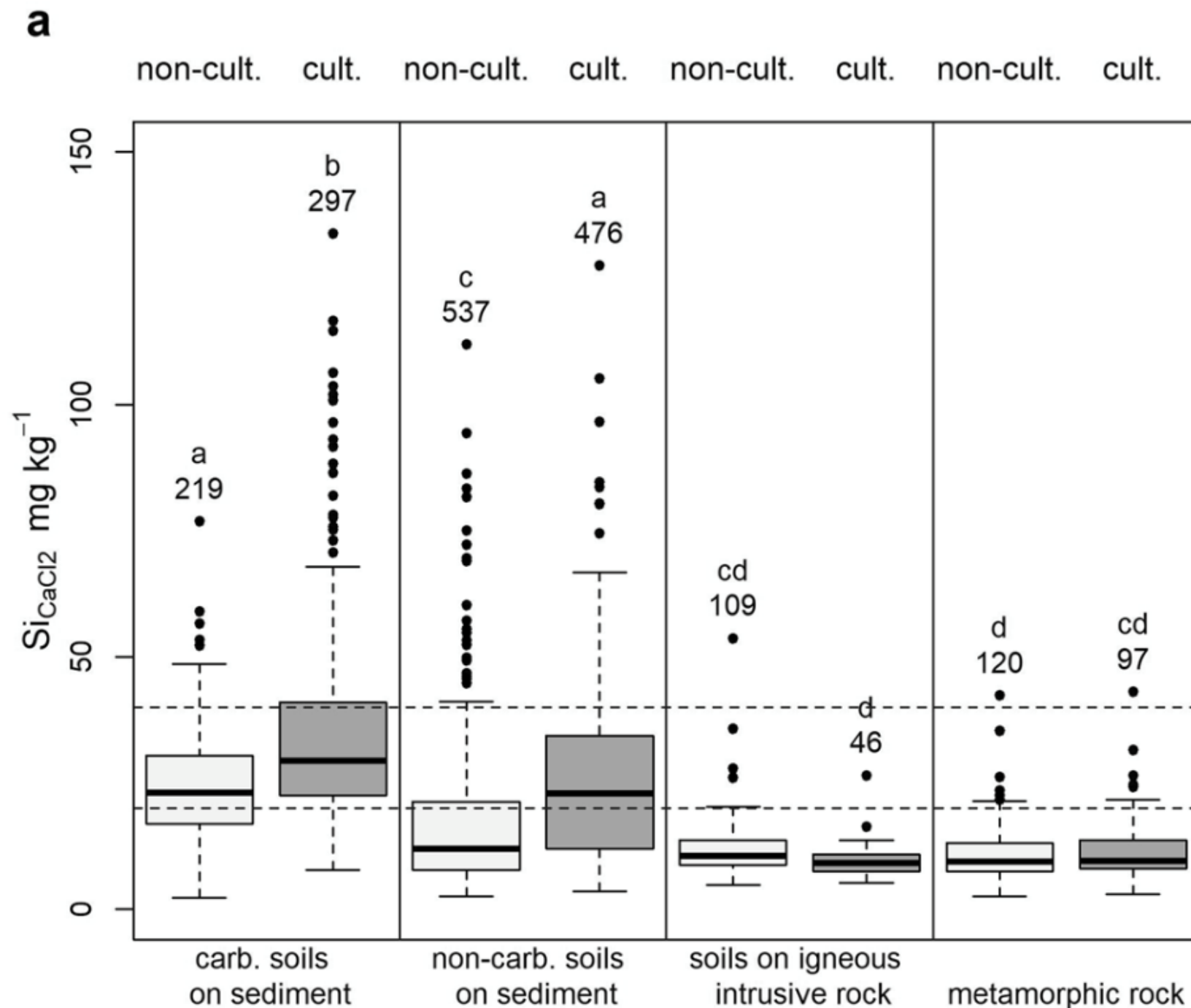
Abstract. Over the past thirty years, the silicon cycle at the scale of continental ecosystems has become an important topic within the scientific community. Since the 1990s, this research has been driven primarily by growing awareness of the need to quantify the impact of anthropogenic activities on the environment, as well as by advances in understanding the beneficial role of silicon in cultivated plants and its application in agricultural practices. This review highlights the major developments in the study of the silicon cycle at the soil-plant scale since the pioneering work of Bartoli, particularly his cycle model (Bartoli, F. *Environ. Biogeochem. Ecol. Bull.* **35** (1983), pp. 469–476).

Phytoliths are now recognized as key players in the silicon cycle at both local and global scales.

**2011 sites du Réseau de
Mesures de la Qualité des
Sols (RMQS) : sols cultivés
vs non cultivés**

**➡ $\text{Si}_{\text{CaCl}_2}$ peut
être plus élevé en
zone cultivée**

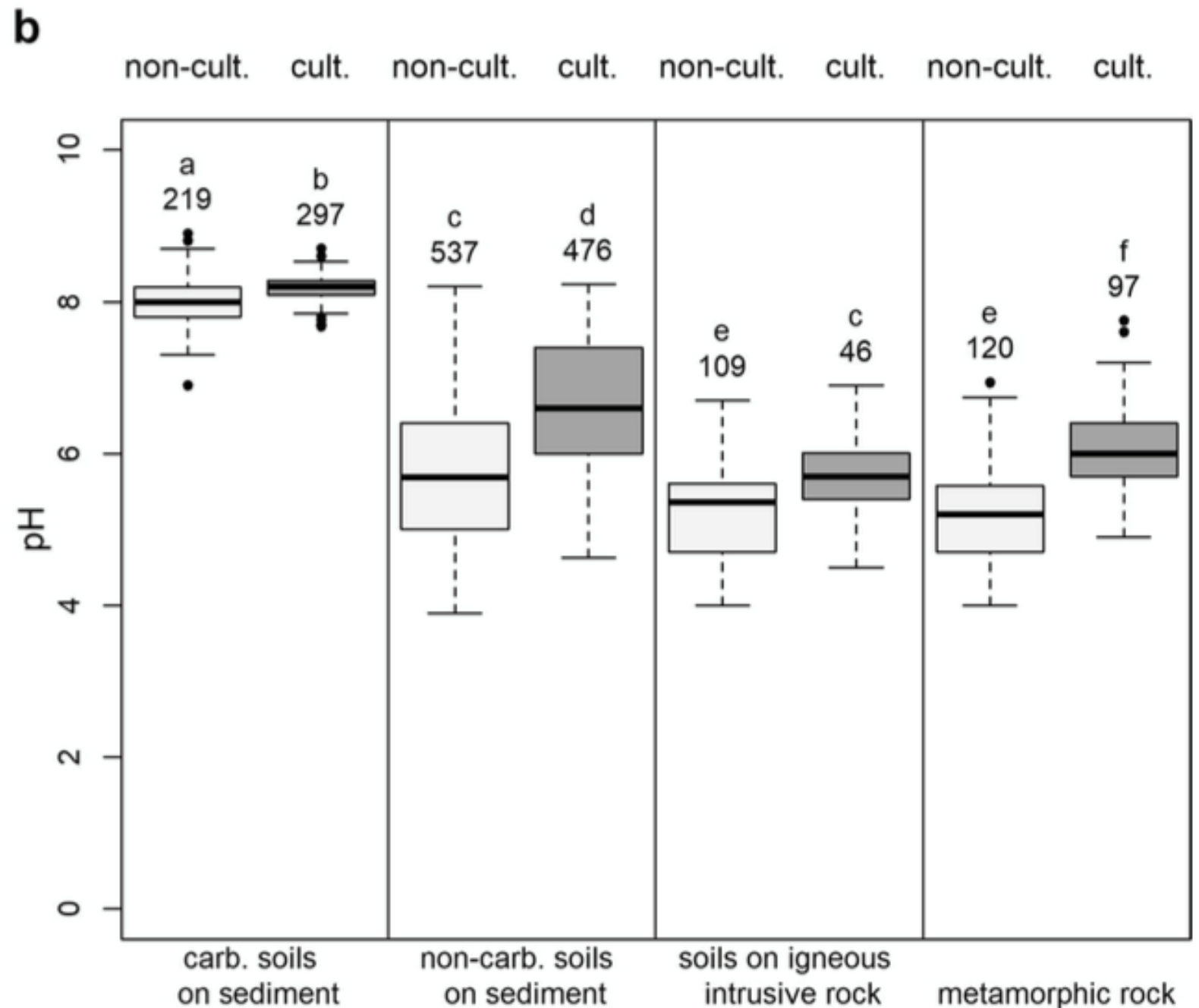
**Caubet, Cornu, Saby,
Meunier (2020, Scientific
Reports projet ANR
BIOSiSOL)**



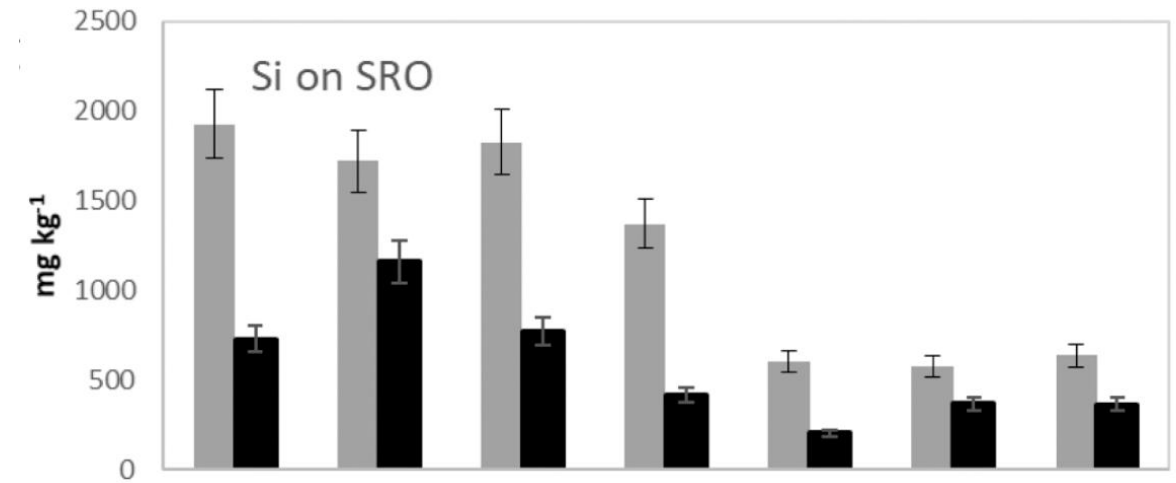
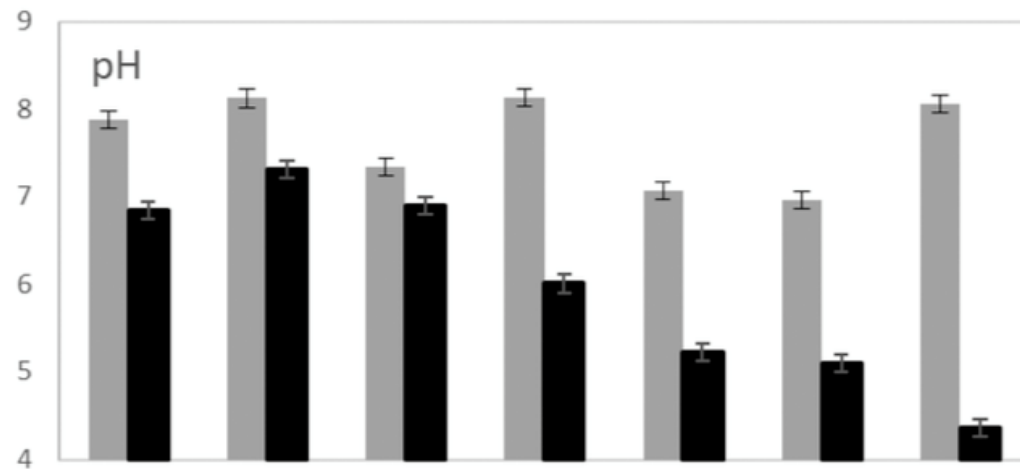
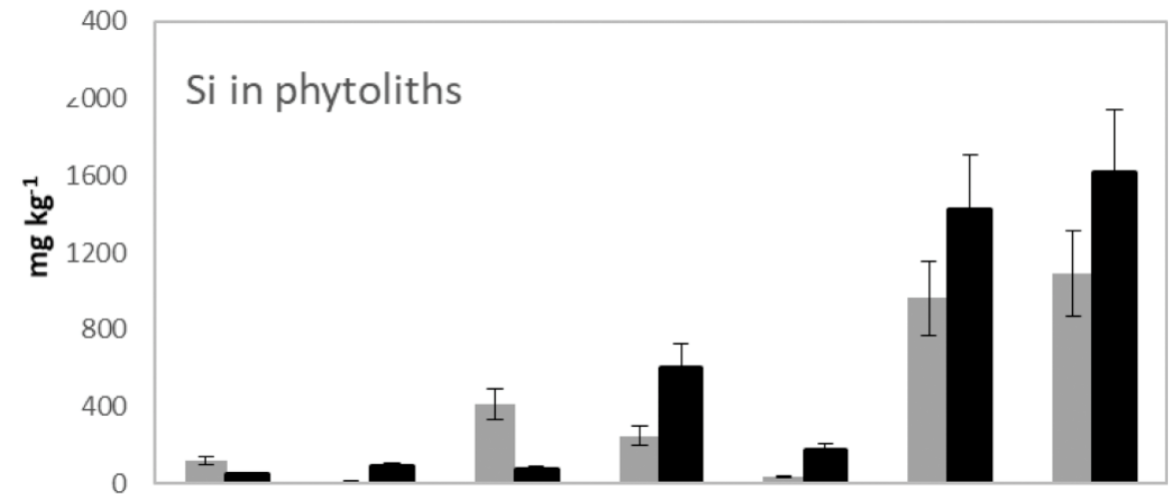
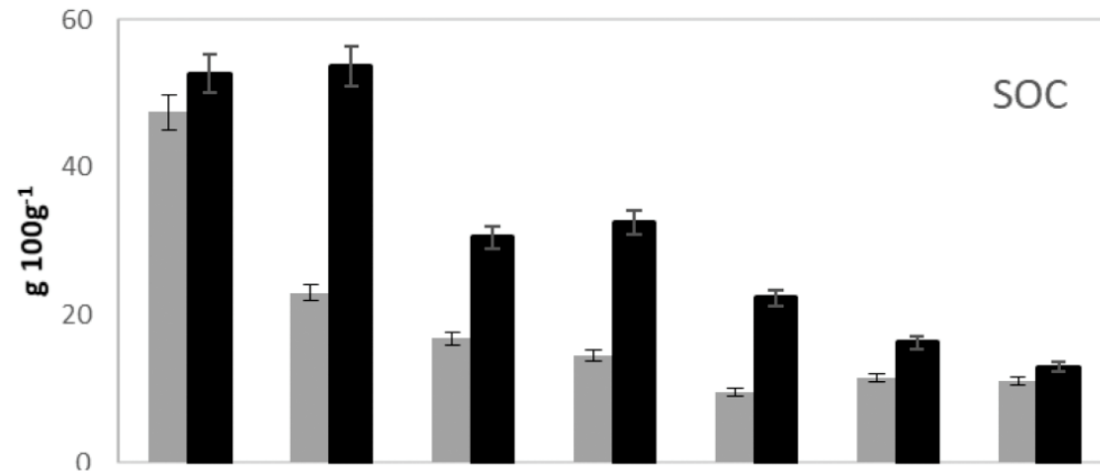
2011 sites du Réseau de Mesures de la Qualité des Sols (RMQS) : sols cultivés vs non cultivés

 pH plus élevé en zone cultivée

Caubet, Cornu, Saby, Meunier
(2020, Scientific Reports projet ANR BIOSISOL)



Gris: sols cultivés
Noir: sols forestiers



calcaric cambisol 701 calcaric cambisol 755 hypereutric cambisol 1166 hypereutric cambisol BS2 albeluvisol luvisol 340 luvisol 62

Cornu et al., Geoderma (2022, projet ANR BIOSiSOL)

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Compagnies membres

Les programmes de l'Institut International de la nutrition des plantes (IPNI) sont financés par des compagnies membres dédiées à l'utilisation efficace et responsable des fertilisants dans la nutrition des plantes. Les bailleurs de fonds de IPNI sont à l'origine des producteurs de un ou plus d'un élément nutritif majeur... azote, phosphate, potasse et le soufre.


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Arab Potash Company


BHP Billiton

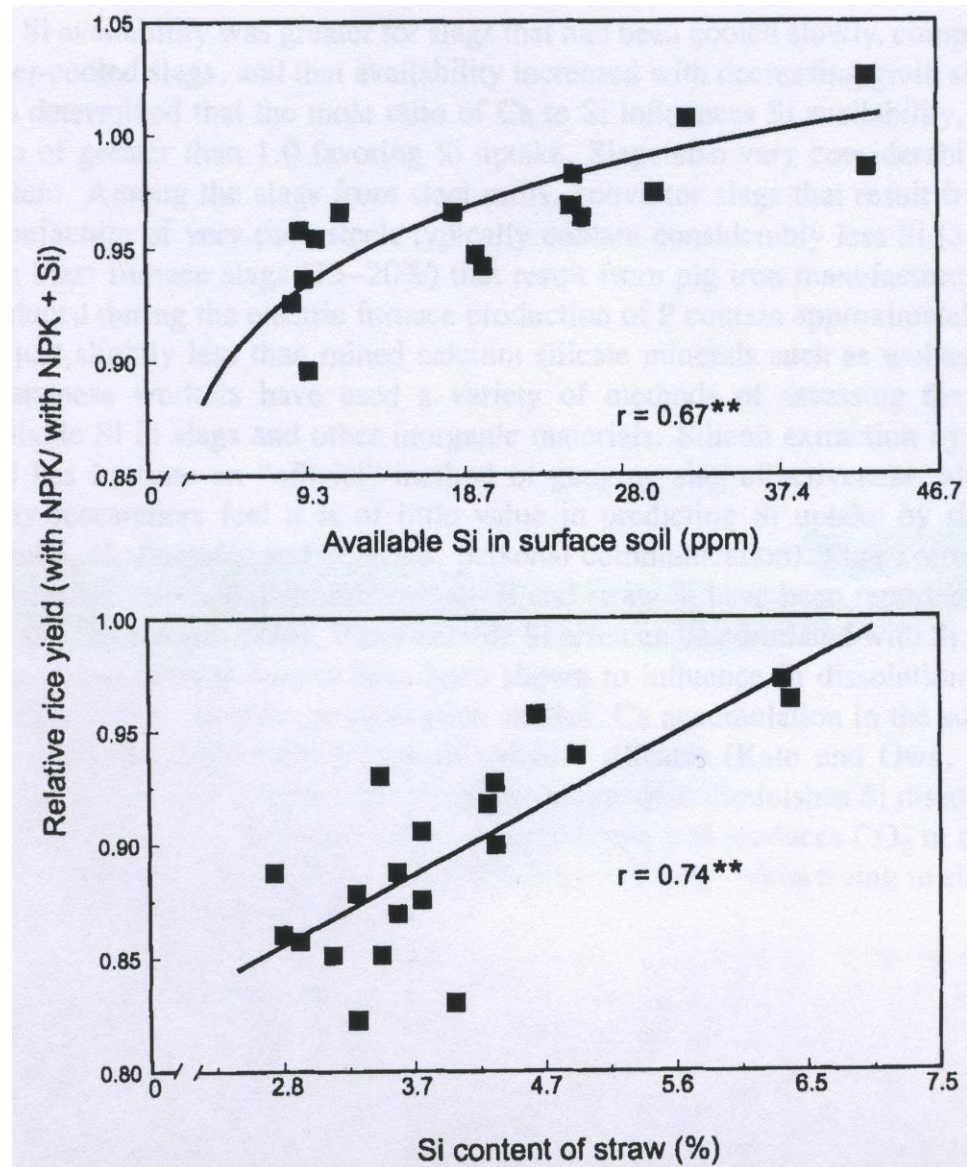

CF Industries Holdings, Inc.


Compass Minerals Plant


International Raw


K+S KALI GmbH


LUXI Fertilizer Industry



Lian, 1976

le riz

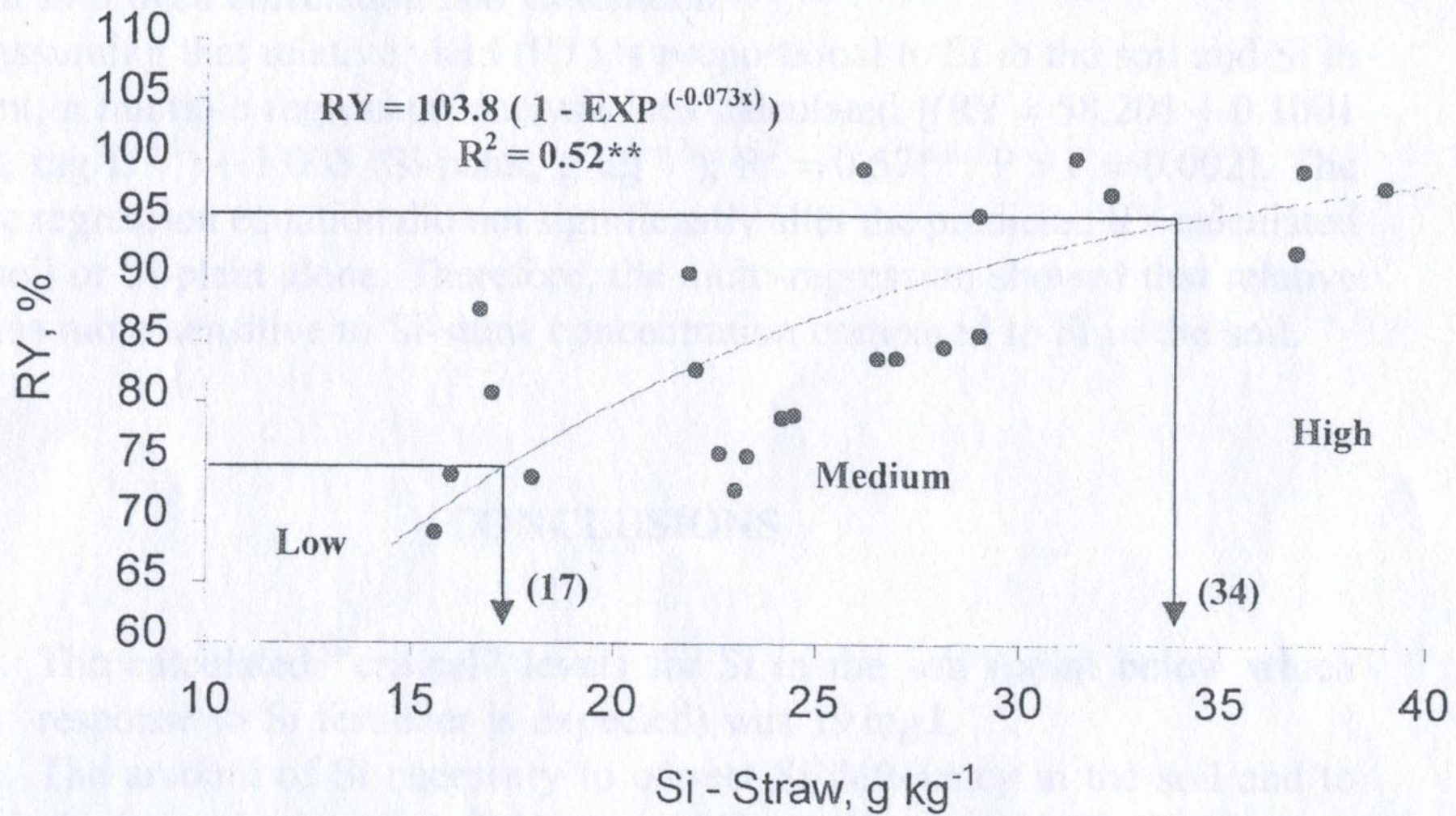
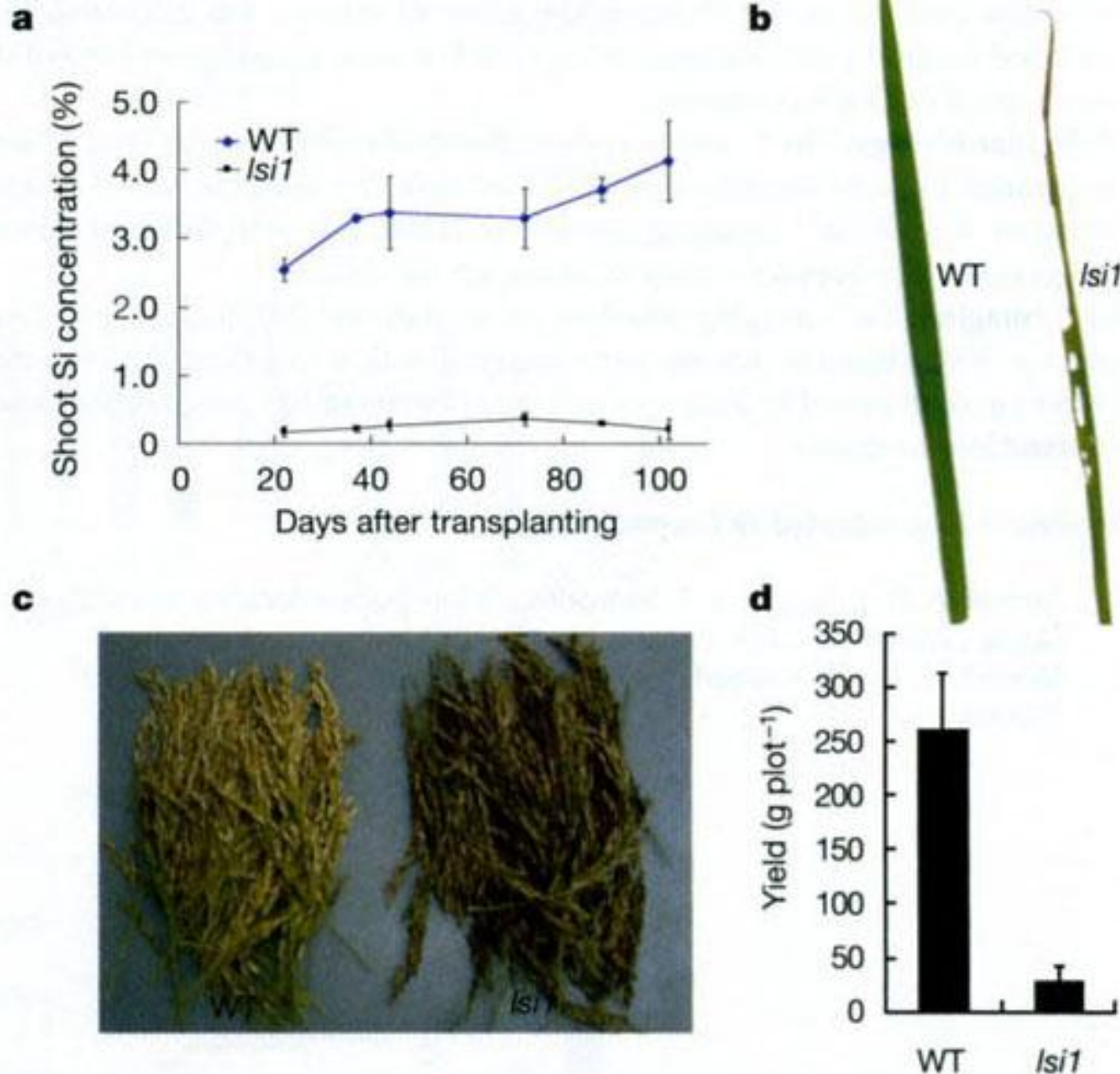


Figure 3. Relationship between Si in the straw at harvest and relative yield (RY) for rice grown in the EAA (Histosol).



-> Absorption active

Le gène *Lsi1* contrôle l'accumulation de silicium dans le riz ; il code une protéine membranaire similaire aux protéines de canaux hydriques (aquaporine) et s'exprime dans les racines.

Ma et al., 2006

Table 2

Pearson correlation coefficient between $\text{Si}_{\text{CaCl}_2}$ and Si_{tot} in French topsoils.
Significance levels: ***: $p\text{-value} < 0.001$; **: $p\text{-value} < 0.01$; *: $p\text{-value} < 0.05$.

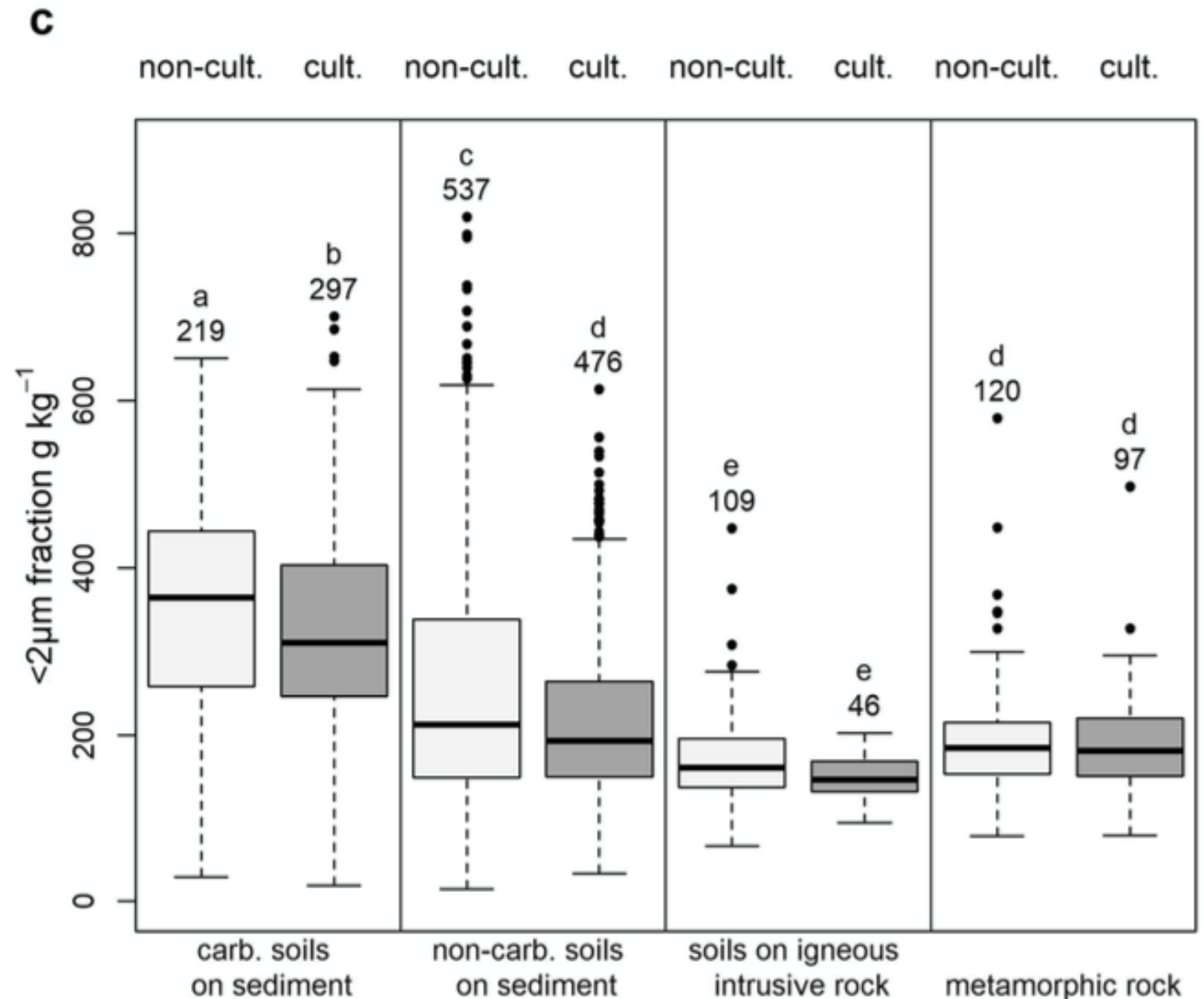
Classes	n	r
Carbonated soils on sediments	508	0.12***
Soils on igneous extrusive rocks	28	−0.25
Soils on igneous intrusive rocks	155	−0.16*
Soils on metamorphic rocks	217	−0.26***
Non-carbonated soils on sediments	1020	−0.41***
Podzols	58	−0.75***
All data	1986	−0.32***

2011 sites du Réseau de Mesures de la Qualité des Sols (RMQS)

2011 sites du Réseau de Mesures de la Qualité des Sols (RMQS) : sols cultivés vs non cultivés

➡ $<2\mu\text{m}$ peut être plus élevée en zone cultivée

Caubet, Cornu, Saby, Meunier (2020, Scientific Reports projet ANR BIOSISOL)



Caubet,
Cornu,
Saby,
Meunier
(2020,Sci
Rep; projet
ANR
BIOSiSOL)

Soil parent material/type	Land use	Si _{CaCl2} (mg kg ⁻¹)					n
		Mean	Sd	Q25	Q50	Q75	
Carbonated soils on sediment	All	31	17	20	26 ^a	36	516
	Non-cultivated	25	11	17	23	30	219
	Cultivated	35	20	23	29	41	297
Soils on igneous extrusive rock	All	51	27	32	47 ^b	66	29
Soils on igneous intrusive rock	All	11	5.7	8.6	10 ^c	13	155
	Non-cultivated	12	6.1	8.8	11	14	109
	Cultivated	10	4.2	7.6	9.3	11	46
Soils on metamorphic rock	All	11	5.8	7.8	9.6 ^c	13	217
	Non-cultivated	11	5.8	7.5	9.5	13	120
	Cultivated	12	5.9	8.1	9.7	14	97
Non-carbonated soils on sediment	All	20	15	9.2	16 ^d	28	1013
	Non-cultivated	16	13	7.9	12	21	537
	Cultivated	25	16	12	23	34	476
Podzols	All	5.1	2.8	3.7	4.2 ^c	4.9	56
All data (subset 1)		21	16	9.5	17	28	1986