



HAL
open science

Impact of antibiotics from pig slurry on the basidiomycete *Trametes versicolor* and on soil microbial communities

Angélique Igel-Egalon, Nathalie Cheviron, Mickael Hedde, Guillermina Hernandez Raquet, Christian Mougin

► To cite this version:

Angélique Igel-Egalon, Nathalie Cheviron, Mickael Hedde, Guillermina Hernandez Raquet, Christian Mougin. Impact of antibiotics from pig slurry on the basidiomycete *Trametes versicolor* and on soil microbial communities. *Environmental Toxicology*, 2012, 27 (3), pp.129-136. 10.1002/tox.20623 . hal-02645790

HAL Id: hal-02645790

<https://hal.inrae.fr/hal-02645790>

Submitted on 24 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ISTA 14 - Impact of antibiotics from pig slurry on soil microbial communities, including the basidiomycete *Trametes versicolor*

Running head: Impact of antibiotics from pig slurry on micro-organisms

Angélique Igel-Egalon¹, Nathalie Cheviron¹, Mickael Hedde¹, Guillermina Hernandez-Raquet² and Christian Mougin¹

¹UR251 Physicochimie et Ecotoxicologie des Sols d'Agrosystèmes Contaminés, INRA, Route de Saint-Cyr, F-78026 Versailles Cedex, FRANCE

²UR050 Laboratoire de Biotechnologie de l'Environnement, INRA, Avenue des Etangs, F-11100 Narbonne, FRANCE

Abstract

Livestock slurry containing antibiotics is a source of contamination of agricultural soils, with possible effects on soil function and micro-organisms. Extracellular oxido-reductases and hydrolases from the fungus *T. versicolor* and fungal growth were monitored in liquid cultures in the presence of tetracycline, lincomycine, sulfadiazine and ciprofloxacin for 10 days, in order to assess the suitability of these enzymes as biomarkers. Among the conditions of treatment, statistical analysis demonstrated an increase in manganese-dependent peroxidase after exposure to sulfadiazine at 1 mg/L when compared to the control. Acid phosphatase activity was decreased by lincomycine at 1 or 10 mg/L. Conversely, β -glucosidase activity increased in the presence of this antibiotic at 10 mg/L. In Terrestrial Model Ecosystems spiked with contaminated pig slurry, lincomycine at the concentration of 8 or 80 $\mu\text{g}/\text{kg}$ dry soil, and ciprofloxacin at 250 ng/kg dry soil decreased the activity of soil dehydrogenase, when compared to a green slurry treatment, over 28-day incubations. Laccase activity was similarly decreased in the presence of the highest concentration of antibiotics. We determined bacterial and fungal biomasses using Q-PCR. Bacterial biomass was increased in the presence of lincomycine at 80 $\mu\text{g}/\text{kg}$ whatever the time of exposure, and to a lesser extent in the presence of ciprofloxacin at 250 ng/kg, but only at day 28. In contrast, both antibiotics, whatever their concentrations, did not modify fungal biomass in soil. In conclusion, we were unable to demonstrate important effects of antibiotics at concentrations found in the agricultural environment.

Keywords: veterinary medicine, pig slurry, enzymes, biomarkers, soil micro-organisms

INTRODUCTION

Antibiotics, which are used worldwide for the treatment of microbial infections, and thus as growth promoters, are administered in large amounts to livestock. Most of these veterinary medicines are excreted from in faeces, which are often used for the fertilization of agricultural soils (see the reviews by Kemper, 2008; Sarmah *et al.*, 2006; Thiele-Bruhn, 2003). Tetracycline, lincomycine, sulfadiazine and enrofloxacin (the later converted to its metabolite ciprofloxacin, Zhou *et al.*, 2008) are compounds frequently used in pig rearing. As a consequence, residues of these chemicals have been discovered in slurry-amended or manured soils in concentrations up to 900,000 ng/kg for tetracycline, 8,500 ng/kg for lincomycine, 1,000 ng/kg for sulfadiazine and 52,000 ng/kg for ciprofloxacin (Kemper, 2008). Their persistence in soils often varies mainly from several days to several months. Although natural antibiotics are released by micro-organisms in soils, unwanted ecotoxicological effects due to exogenous chemicals, such as alteration of microbial turnover processes in soils and spreading of antimicrobial resistance genes among environmental bacteria, can be expected (Kemper, 2008). It is thus important to understand the effects of pharmaceutical antibiotics on soil micro-organisms, particularly concerning lincomycine and ciprofloxacin, whose fates and effects in soils have been poorly studied to date.

One reason for our lack of knowledge is the death of efficient tools to assess the impacts of chemicals on the functional diversity of micro-organisms in soils. It is thus necessary to understand the molecular basis for the enzymatic secretion and to develop selective and sensitive biomarkers for the ecotoxicity assessment of soils. Fungal liquid cultures allowing high contaminant bioavailability appear suitable for that purpose. The white-rot basidiomycete *Trametes versicolor* has been studied for many years for its suitability to produce biomarkers for soil ecotoxicity assessment (Mougin *et al.*, 2003). For example, its laccases have been shown to be induced after exposure to environmental contaminants such as pesticides and polycyclic aromatic compounds (Mougin *et al.*, 2002). Lebrun *et al.* in 2010 demonstrated that the activities of several enzymatic systems of this fungus were affected after exposure to copper.

Secondly, the standard tests for toxicity assessment of antibiotics are often conducted under unrealistic conditions. As integrated systems, Terrestrial Model Ecosystems, where natural parameters (moisture, temperature...) can be controlled in order to reduce the variability during the assays, offer more realistic manure application conditions to assess both the environmental fate and effects of chemical contaminants on different soil communities (Ghanem *et al.*, 1996; Fernandez *et al.*, 2004, Boleas *et al.*, 2005).

The goals of our programme are to investigate the impact of manure treatment and storage on its antibiotic content, the fate of antibiotics in slurry-amended and manured soils, and the resulting effects of these medicines on the organisms in the topsoil.

In the present study, our specific objectives are 1) to assess the suitability of fungal biomarkers to monitor the effects of antibiotics in liquid cultures and 2) to assess the ecotoxicity of selected antibiotics on the indigenous microflora in soils amended with pig slurry through functional and structural parameters determined in Terrestrial Model Ecosystems. We provide new information concerning the impact of antibiotics on soil micro-organisms in simulated agricultural situations.

MATERIALS AND METHODS

Chemicals and Reagents

Antibiotics and all other high purity chemicals (>99%): e.g. tetracycline (TET), lincomycine (LIN), sulfadiazine (SDZ) and ciprofloxacin (CIP), were purchased from Sigma-Aldrich-Fluka (France). Analytical grade solvents were obtained from Carlo-Erba (France).

Soil characteristics

The silt loam was collected in the 10–20 cm layer of an experimental site (La Cage, INRA, Versailles, France). It comprises 21.6% sand, 61.1% silt, and 17.3% clay. Its content in organic carbon is 0.98%, and its pH_{wat} was 7.1. Its water holding capacity (WHC) was $15.64 \pm 0.21\%$ at $\text{pF}=2.5$ and $6.79 \pm 0.21\%$ at $\text{pF}=4.2$. The soil was roughly homogenized, sieved at 2 mm, and used without storage for the preparation of the Terrestrial Model Ecosystems (TMEs).

Pig slurry sampling and characterisation

The pig slurry, referred to here as green slurry, was from the quarantine livestock building of the IFIP (French Pig Institute) at Romillé (Brittany, France). The animals were cross-bred from Large White and Landrace and weighed 40-100 kg (fattening pigs). They were fed an unchanging cereal formula consisting of wheat (44%), barley (30%), soybeans (18%), molasses (2%) and amino acids and minerals (6%). They did not receive antibiotics.

The pig slurry resulting from about three months of manure accumulation from 20 pigs was homogenized in the pit (about 25 m³) using a submersible pump for about 20 minutes. Then 20 litres of slurry were collected and stored at 4°C for one day until use.

The slurry pH (7.5), dry matter content (26.2 +/- 0.1 g/kg), Chemical Oxygen Demand (36 +/- 2 gO₂/L), Total Kjeldahl Nitrogen (3.05 +/- 0.03 g/kg) and Total Ammonia-N (2.3 +/- 0.1 g/kg) were determined according to standard methods (APHA, 1992). All parameters were analysed in

triplicate. These data are in agreement with previous reports on pig slurry characterisation in French husbandry (Burton and Turner, 2003).

Micro-organism and culture conditions

Trametes versicolor ATCC 32745 was grown on the culture medium described by Abadulla *et al.* (2000), containing glucose (10 g/L) and NH₄CL (2.5 g/L) as carbon and nitrogen sources. The medium also contained 0.5 g/L MgSO₄ 7H₂O, 5 g/L yeast extract, 0.1 g/L CaCl₂ and 0.5 g/L KCl. FeSO₄, ZnSO₄, MnSO₄ and CuSO₄ were added to achieve the final concentration of 0.01 g/L. A mycelial mat on agar plug (10 mm diam.) was inoculated into 10 mL of the culture medium in each 150 mL Erlenmeyer flask. Cultivation was carried out statically in the dark at 25°C for 10 days. Solutions of antibiotics in water (TET, LIN), diméthylformamide (SDZ) and dimethylsulfoxide (CIP) were added to the cultures to give 0.1, 1 and 10 mg/L (100 µL solution per Erlenmeyer flask). Biomass and enzymatic determinations were achieved at the beginning of the incubations, then after 3, 5, 7 and 10 days. Each experiment was performed in triplicate.

Set up of Terrestrial Model Ecosystems

Three days before the beginning of the experiments, each Terrestrial Model Ecosystem (TME) was filled with 1 kg dry soil moistened to 50% of its WHC. The soil was then amended with 25 mL pig slurry to simulate agronomic conditions (equivalent to 30 T dry manure/ha). Slurry was spiked or not with antibiotics. CIP was added to the final concentrations of 1 and 10 µg/L in the slurry, 25 and 250 ng/kg in dry soil. LIN was applied in final concentrations of 320 and 3200 µg/L in slurry, equivalent to 8 and 80 µg/kg in dry soil. After mixing, the amended soil was set in the TMEs, a litter-bag (7 x 7 cm, 2 g dry wheat straw) was inserted at mid-height of the soil, and water was added to achieve 100% WHC. TMEs were incubated in the dark at 18 ± 1°C. Biomass and enzyme activities were measured at the beginning of incubation, then after 7, 14 and 28 days. After 28 days, the bags were removed, washed, dried and the straw was weighted. Each experiment was performed in triplicate.

Enzyme activity measurements

Laccase (LAC; E.C. 1.10.3.2) production was assessed in liquid cultures of *T. versicolor* by measurement of enzymatic oxidation of 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid)(ABTS) at 420 nm ($\epsilon_{420} = 3.6 \times 10^4 \text{ cm}^{-1} \text{ M}^{-1}$) according to Wolfenden & Wilson (1982). The reaction mixture contained 20 µL extracellular fluid and 980 µL 1 mM ABTS in 0.1 M KH₂PO₄/citric acid buffer (pH 3.0) at 30°C. The buffer solution was saturated with air by bubbling prior to the experiment. Manganese-dependent peroxidase (MNP; E.C. 1.11.1.14) activity was

monitored by the oxidation of 20 μL 5 mM 4-(4-hydroxy-3-methoxyphenyl)-3-buten-2-one at 334 nm, 200 μL extracellular fluid, 20 μL 5 mM MnSO_4 , 20 μL 16mM hydrogen peroxide in 740 μL 0.1 M KH_2PO_4 /citric acid buffer (pH 5.0), as described by Paszczynski *et al.* (1986). One unit of enzyme activity is defined as the amount of enzyme that oxidises one μmol ABTS per min.

In TMEs, we used a protocol adapted from Floch *et al.* (2007) to determine laccase activity. The reaction mixture contained 1mL soil solution (obtained from 1 g soil in 6 mL KH_2PO_4 /citric acid buffer pH 3.0), and 600 μL of a 50 mM guaiacol solution. After incubation at 37 °C for 20 min, the mixture was centrifuged at 12000 rpm at 4 °C for 2 min. The formation of tetrameric guaiacol in the supernatant was measured at 470 nm.

Measurement of dehydrogenase activity (DHA; E.C. 1.1.1.1), indicating the level of global metabolic process in the soil, was adapted from Schaefer (1963). 1 mL distilled water and 250 μL aqueous solution of 1,3,5-triphenyltetrazolium chloride (TTC) at 40 g/L were mixed with 1 g fresh soil in 30-mL centrifuge tubes. Controls were prepared without TTC. Incubation was performed at 37°C for 16 hours. After that period, 5 mL ethanol was added to the mixture which was shaken for 5 min in the dark. The medium was incubated at 37°C for 2 hours, and shaken after one hour. Finally, TTC was added to the control and all the mixtures were centrifuged 5 min at 6000 g. The absorbance of the supernatant (red colour in case of formazan formed) was measured at 485 nm. Results were expressed in mU per g dry soil.

Acid phosphatase (ACP; E.C. 3.1.3.2, β -glucosidase (GLU; E.C. 3.2.1.21) activities were measured according to a method adapted from Dick (1997). 16 g soil were shaken in 100 mL distilled water. Then, 125 μL of soil suspension were incubated with 25 μL 0.05 M substrate (4-nitrophenyl phosphate for the phosphatase or 4-nitrophenyl β -D-galactopyranoside for the glucosidase) at 37°C for one hour in multiwell plates. For each soil sample, a control without substrate was performed. At the end of the incubation, 25 μL of CaCl_2 (0.5 M) were added in order to stabilize humic acid, and 100 μL Tris 0,1 M pH12 were used to stop the reaction. The amount of p-nitrophenol (PNP) formed was obtained by the measurement of the supernatant absorbance at 405 nm. Results were expressed in mU per g dry soil.

Biomass determination

Biomass was determined from soil genomic DNA. Total genomic DNA was extracted from 0.5g of frozen soil using the Fast DNA kit for soil (MP Biomedical) and suspended in 100 μL of sterile deionised water. rDNA was then amplified in 20 μL final qPCR mixture containing the following total amounts: 10 ng of total soil DNA, 25 pmoles of each primer, 10 μL of iq-SYBR®Green super Mix (Biorad). For bacterial 16S-rDNA, the forward primer used was S-BCT 5'-CAG GCC TAA CAC ATG CAA GTC-3' (primer 63f from Marchesi *et al.*, 1998) and the reversed primer was AS-

BCT1 5'-CTG CTG CCT CCC GTA GG-3' (primer 341F from Muyzer *et al.*, 1993). For fungal 18S-rDNA, the forward primer was S-FUN1 5'-GGA AAC TCA CCA GGT CCA GA-3' (primer nu-SSU-1196 from Borneman and Hartin, 2000) and the reversed primer was AS-FUN1 5'-ATT GCA ATG CYC TAT CCC CA-3' (primer nu-SSU-1536 from Borneman and Hartin, 2000). All cycles were programmed on Chom4 (Biorad) to perform 35 cycles consisting of: 95°C for 40s, 64°C for 45s and 72°C for 30s with bacterial rDNA and 95°C for 20s, 62°C for 30s and 72°C for 30s with fungal rDNA. Each amplification was followed by a final extension step of 10 minutes at 72°C.

Data analysis

Prior to statistical analyses, Shapiro and Bartlett tests were used to verify the normality and the homoscedasticity of the data, respectively. If both hypotheses were not refuted, ANOVAs and Tukey significant differences test were performed. In all other cases, equivalent non-parametric tests were preferred (Kruskall-Wallis and Kolmogorov-Smirnov tests, respectively).

For liquid culture results, two-way ANOVA was used to test the effect of “exposure time” and “antibiotic concentration” factors on fungi biomass and enzyme activities. Exposure times were 0, 3, 5, 7 and 10 days. The concentration levels were 0 (*i.e.* the corresponding control), 0.1, 1 and 10 mg/L for all antibiotics. When ANOVA was significant, Tukey HSD tests for mean comparison were realized. Similar analyses were made for TMEs with “exposure time” (0, 7, 14 and 28 days) and the “antibiotic concentration” as the independent variables. The spread concentrations were 0 (control), 8 and 80 µg/kg dry soil for lincomycine and 0 (control), 25 and 250 ng/kg dry soil for ciprofloxacin. All tests were realized with R software (R core development team, 2009) at the rejection level $\alpha = 0.05$.

RESULTS AND DISCUSSION

Impact of antibiotics on *T. versicolor* cultured in liquid conditions

The effects of incubation time and antibiotic concentration on *T. versicolor* cultured in liquid conditions have been assessed on fungal growth and activities of extracellular oxido-reductases (laccase, LAC; Mn-dependant peroxidase, MNP) and hydrolases (β -glucosidase, GLU; acid phosphatase, ACP). Levels of medium spiking (0.1, 1 and 10 mg/L) were chosen to cover a range of values previously reported to modify fungal protein activity. Considering overall effects, most of the variance in data was explained by exposure time (Table 1). Bell-shape curves were observed, with maxima noticed after 5 days for fungal biomass, and after 7 days for extracellular hydrolases. In contrast, LAC activity presented two peaks, after 3 and 10 days of exposure, whereas MNP

activity increased during the course of incubation with maxima noticed after 10 days. These results are consistent with the previous study of Lebrun *et al.* (2010).

On the other hand, few statistical differences appeared when regarding the effect of antibiotic concentration on the enzymatic activities used as biomarkers. TET and CIP from 0.1 to 10 mg/L did not exhibit any impact on the selected activities in our experimental conditions. It remains noteworthy that the well known inducer xyloidine (Kollmann *et al.*, 2005), used as a positive control in the present experiments, led to a 13-fold increase of LAC after 3 days of fungal exposure. SDZ presented an effect only on MNP, with higher activities in 1 mg/L concentration treatment than in other cases (Figure 1). LIN significantly influenced both ACP and GLU. The activity of ACP was decreased when the antibiotic was brought at 1 or 10 mg/L (*e.g.* -34% at the peak of activity, $p < 0.05$)(Figure 2A). Conversely, GLU activity increased in the presence of LIN at 10 mg/L when compared to the control (+10%, $p < 0.05$)(Figure 2B).

Our knowledge of the possible effects of antibiotics on filamentous environmental fungi is scarce. Because of their molecular mode of action, it was unlikely that the antibiotics in the present study exert direct effects on *T. versicolor*. Nevertheless, Dhawan *et al.*, (2005) demonstrated that TET at 200 mg/L inhibited fungal growth and increased laccase production from *Cyathus bulleri* and *Pycnoporus cinnabarinus*. Because environmental contaminants (PAHs, pesticides, Mougine *et al.*, 2003; xyloidine, Kollmann *et al.*, 2005) modify the secretion of enzymes from *T. versicolor*, they were intended to be used as potential biomarkers for ecotoxicity assessment. Our results show that fungal oxido-reductases and hydrolases do not behave as relevant biomarkers of exposure to antibiotics. That poor sensitivity could be due to the ability of white rot basidiomycetes to secrete extracellular lignin-degrading enzymes efficiently degrading antibiotics, as reported for TET (Wen *et al.*, 2009).

Impact of antibiotics on soil functional diversity in Terrestrial Model Ecosystems

LIN and CIP are two antibiotics widely quantified in French slurry or manure samples (our programme, but also data reported by Kuchta and Cessna, 2009; Zhou *et al.*, 2008). Our knowledge of the effects of these chemicals on soils organisms is scarce. We observed a slight effect of LIN on the ACP and GLU activities of *T. versicolor*. CIP was recently described to affect bacterial communities in soils (Zhou *et al.*, 2008). Here we studied their effects in TMEs filled with a silt loamy soil supplemented by green or spiked slurry samples, each applied at 30T/ha. Final concentrations used in our study, of agricultural relevance, were 8 and 80 $\mu\text{g/kg}$ dry soil for LIN, 25 and 250 ng/kg dry soil for CIP. Modification of soil functional biodiversity was assessed by enzyme activity measurements (LAC, DHA, GLU, ACP).

Among enzymatic activities, two patterns of response appeared, according to the type of enzyme, which were shared by the two antibiotics. Hydrolase enzymes merely responded to the time of incubation, as shown by the evolution of activities of ACP and GLU in our TMEs. For instance, in the presence of LIN, GLU activity was influenced by the time exposure ($F_{3,32} = 25.7$, $p < 0.001$ and $F_{3,32} = 19.1$, $p < 0.001$) but not by antibiotic concentration ($F_{3,32} = 2.8^{ns}$ and $F_{3,32} = 0.8^{ns}$) (Figure 3).

In contrast, oxydo-reductases were influenced by antibiotic concentration rather than time of incubation. The activity of DHA was constant during the course of the experiment with green slurry. It was affected by the presence of each of the antibiotics. Spreading LIN-containing slurry decreased the activity of DHA, either at 8 or 80 $\mu\text{g}/\text{kg}$, in comparison with green slurry alone (Figure 4A). For instance, after 7 days of incubation, DHA activity was half lower (-54%) in the LIN-80 $\mu\text{g}/\text{kg}$ treatment, than in green slurry one. Regarding CIP effects, only treatment spread at the highest concentrations induced a significant decrease in DHA activity (Figure 4B). For instance, after 7 days, DHA activity in CIP-250 ng/kg treatment was decreased by 45% when compared to green slurry treatment.

LAC activity was similarly decreased in the presence of the highest concentration of antibiotics (data not shown). For example, in the LIN-80 $\mu\text{g}/\text{kg}$ treatment, activities after 7 and 14 days were 34% and 23% lower, respectively, than in the control. In the CIP-250 ng/kg treatment, decreases were comparable for the same exposure times (-25% and -40% respectively). Nevertheless, after 28 days no differences were observed between treatments.

Whatever the incubation conditions, 18-24% of the initial amounts of straw were degraded in the litter-bag assays, without a significant effect of the antibiotics (data not shown).

Data concerning the effects of LIN and CIP on soil enzyme activities are lacking. Our results contrast with the study of Zhou et al. (2008), who reported no impact of enrofloxacin and its metabolite CIP on populations of soil micro-organisms at concentrations below 0.2 mg/kg . It should be noted that the effects of antibiotics in soils are influenced by their bioavailability for micro-organisms.

Impact of antibiotics on soil microbial biomass in Terrestrial Model Ecosystems

In our experiments, bacterial and fungal biomasses were specifically determined using Q-PCR on DNA from soil samples. Bacterial biomass was affected by spreading with antibiotic spiked-slurry. It was increased in the presence of LIN at 80 $\mu\text{g}/\text{kg}$ whatever the time of exposure (Figure 5A), and to a lesser extent in the presence of CIP at 250 ng/kg , but only at day 28 (Figure 5B). In contrast, LIN and CIP, whatever their concentrations, did not modify fungal biomass in soil TMEs. No data are available to date concerning the effects of LIN on microbial communities in agricultural soils. However, recent laboratory experiments demonstrated contrasted shifts in bacterial diversity

according to pH in forest soils (Cermak et al., 2008). Only one study (Zhou *et al.*, 2008) reported an impact of enrofloxacin and its metabolite CIP on the edaphon community, leading to the promotion of bacterial growth utilizing the fluoroquinolones as a nutrient source. Antibiotics (*e.g.* sulfonamide, SDZ and tetracycline compounds) increased the fungal:bacterial ratio, although in higher concentrations within the soil (Hammesfahr et al., 2008; Thiele-Bruhn and Beck, 2005).

Acknowledgements: The present study, as a part of the research programme DIPERPHA, was supported by the French ANR programme SEST and by ADEME. We are grateful to Dr. Patrick Dabert (GERE unit, CEMAGREF, Rennes, France) for providing and analysing the samples of green pig slurry. The authors are also indebted to Dr. David Tepfer (PESSAC INRA) for proofreading the manuscript, and to Agathe Brault, Sébastien Breuil and Isabelle Touton for their technical assistance.

REFERENCES

- Abadulla E, Tzanov T, Costa S, Robra KH, Cavaco-Paulo A, and Gübitz GM. 2000. Decolorization and Detoxification of Textile Dyes with a Laccase from *Trametes hirsute*. *Appl Environ Microbiol* 66:3357-3362.
- APHA. 1992. Standard Method for the examination of Water and Wastewater, 18th ed. Washington, DC, American Public Health Association, 1110 p.
- Boleas S, Alonso C, Pro J, Mar Babin M, Fernandez C, Carbonell G and Tarazona J. 2005. Effects of sulfachlorpyridazine in MS 3-arable land: a multispecies soil system for assessing the environmental fate and effects of veterinary medicines. *Environ Toxicol Chem* 24:811-819.
- Borneman J and Hartin RJ. 2000. PCR Primers that Amplify Fungal rRNA Genes from Environmental Samples. *Appl Environ Microbiol* 66:4356-4360.
- Burton CH and Turner C. 2003. Manure Management, Treatment Strategies for Sustainable Agriculture, 2nd ed., Silsoe Research Institute, Wrest Park, Silsoe, Bedford, UK, 451 p.
- Cermak L, Kopecky J, Novotna J, Omelka M, Parkhomenko N, Plhackova K, Sagova-Mareckova M. 2008. Bacterial communities of two contrasting soils reacted differently to lincomycine treatment. *Appl Soil Ecol* 40:348-358.
- Floch C, Alarcon-Gutiérrez E, Criquet S. 2007. ABTS assay of phenol oxidase activity in soil. *J Microbiol Methods* 71:319–324.
- Dhawan S, Lal R, Hanspal M, Kuhad RC. 2005. Effect of antibiotics on growth and laccase production from *Cyathus bulleri* and *Pycnoporus cinnabarinus*. *Bioresource* 96:1415-1418.
- Dick RP. 1997. Soil enzyme activities as integrative indicators of soil health. In: Parkhurst CE, Doube BM, Gupta VVSR, editors. *Biological Indicators of Soil Health*. CAB International, Oxon, United Kingdom, p.121-156.
- Fernandez C, Alonso C, Babin MM, Pro J, Carbonell G, Tarazona JV. 2004. Ecotoxicological assessment of doxycycline in aged pig manure using multispecies soil systems. *Sci Total Environ* 323:63-69.

- Ghanem A, Dubroca J, Chaplain V and Mougin C. 2006. Fate of herbicides and nonylphenol in soil-plant-water systems amended with contaminated sewage sludge. *Environ. Chem. Letters* 4:63-67.
- Hammesfahr U, Heuer H, Manzke B, Small K, Thiele-Bruhn S. 2008. Impact of the antibiotic sulfadiazine and pig manure on the microbial community structure in agricultural soils. *Soil Biol Biochem* 40:1583-1591.
- Kemper N. 2008. Veterinary antibiotics in the aquatic and terrestrial environment. *Ecol Indic* 8:1-13.
- Kollmann ., Boyer FD, Ducrot PH, Kerhoas L, Jolivalt C, Touton I, Einhorn J, and Mougin C. 2005. Oligomeric compounds formed from 2,5-xylydine (2,5-dimethylaniline) are potent inducers of fungal laccases. *Appl Microbiol Biotechnol* 68:251-258.
- Kuchta SL and Cessna AJ. 2009. Fate of lincomycin in snowmelt runoff from manure-amended pasture. *Chemosphere* 76:439-446.
- Lebrun JD, Trinsoutrot-Gattin I, Laval K, Mougin C. 2010. Development phase-depending response of extracellular enzymatic system to copper stress in *Trametes versicolor*. *Environ Toxicol Chem* 29:902-908.
- Marchesi JR, Sato T, Weightman AJ, Martin TA, Fry JC, Hiom SJ and Wade WG. 1998. Design and evaluation of useful bacterium-specific PCR primers that amplify genes coding for bacterial 16S rRNA. *Appl Environ Microbiol* 64:795-799.
- Mougin C, Kollmann A and Jolivalt C. 2002. Enhanced production of laccases by the fungus *Trametes versicolor* by the addition of xenobiotics. *Biotechnol Letters* 24:139-142.
- Mougin C, Jolivalt C, Briozzo P, Madzak C. 2003. Fungal laccases: from structure-activity studies to environmental applications. *Environ. Chem. Letters* 1:145-148.
- Muyzer G, de Waal EC and Uiterlinden AG. 1993 Profiling of complex microbial populations by denaturing gradient gel electrophoresis analysis of polymerase chain reaction-amplified genes coding for 16S rRNA. *Appl Environ Microbiol* 59:695-700.

- Paszczynski A, Huynh VB, Crawford R. 1986. Comparison of ligninase-I and peroxidase-M2 from the white-rot fungus *Phanerochaete chrysosporium*. Arch. Biochem. Biophys. 244:750-765.
- R Development Core Team (2009). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>.
- Sarmah AK, Meyer MT, Boxall ABA. 2006. A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (Vas) in the environment. Chemosphere 65:725-759.
- Schaefer R. 1963. L'activité déshydrogénasique comme mesure de l'activité biologique globale des sols. Annales de l'Institut Pasteur 105:326-331.
- Thiele-Bruhn S. 2003. Pharmaceutical antibiotic compounds in soils – a review. J Plant Nutr Soil Sci 166:145-167.
- Thiele-Bruhn S, Beck IC. 2005. Effects of sulphonamide and tetracycline antibiotics on soil microbial activity and microbial biomass. Chemosphere 59:457-465.
- Wen X, Jia Y, Li J. 2009. Degradation of tetracycline and oxytetracycline by crude lignin peroxidase prepared from *Phanerochaete chrysosporium* - a white rot fungus. Chemosphere 75:1003-1007.
- Wolfenden BS, Wilson RL. 1982. Radical cation as reference chromogens in kinetic studies of one electron transfer reactions. J Chem Soc Perkin Trans II:805-812.
- Zhou X, Chen C, Yue L, Sun Y, Ding H, Lui Y. 2008. Excretion of enrofloxacin in pigs and its effect on ecological environment. Environ Toxicol Pharmacol 26:272-277.

Table 1. Anova results (F values) on the effect of the factors “antibiotic concentration” (0, 0.1, 1 and 10 mg L⁻¹), “exposure time” (0, 3, 5, 7 and 10 days) and their interaction on the response of 5 extracellular enzymatic activities of *T. versicolor* in liquid conditions.

TET: tetracycline, LIN: lincomycine, SDZ: sulfadiazine, CIP: ciprofloxacin, ACP: acid phosphatase, GLU: β-glucosidase, LIP: lignin peroxydase, MNP: manganese peroxydase, LAC: laccase. * p < 0.05; ** p < 0.01; *** p < 0.001.

Antibiotic	Factor	ACP	GLU	LIP	MNP	LAC
TTC	Antibiotic concentration	0.18	1.53	0.08	0.04	0.16
	Exposure time	89.00***	42.84***	5.87*	2.13	12.91***
	Interaction of factor	1.73	2.16	0.83	0.32	2.82
LYN	Antibiotic concentration	0.10	1.95	0.67	0.76	0.04
	Exposure time	62.70***	48.32***	1.56	17.12***	31.33***
	Interaction of factor	0.02	1.90	0.67	0.12	0.06
SDZ	Antibiotic concentration	0.24	0.71	1.05	0.38	0.58
	Exposure time	38.59***	30.60***	3.39	4.99***	12.41***
	Interaction of factor	0.48	0.60	0.62	<0.01	<0.01
CIP	Antibiotic concentration	0.08	0.16	2.00	<0.01	0.04
	Exposure time	106.90***	63.26***	6.44*	6.56*	2.33
	Interaction of factor	0.13	0.28	3.27	0.11	0.04

Fig 1. Effect of sulfadiazine (SDZ) at various concentrations (mg/L) on Mn-dependant peroxidase (MNP) in liquid cultures of *T. versicolor*. Results are expressed as means \pm standard errors.

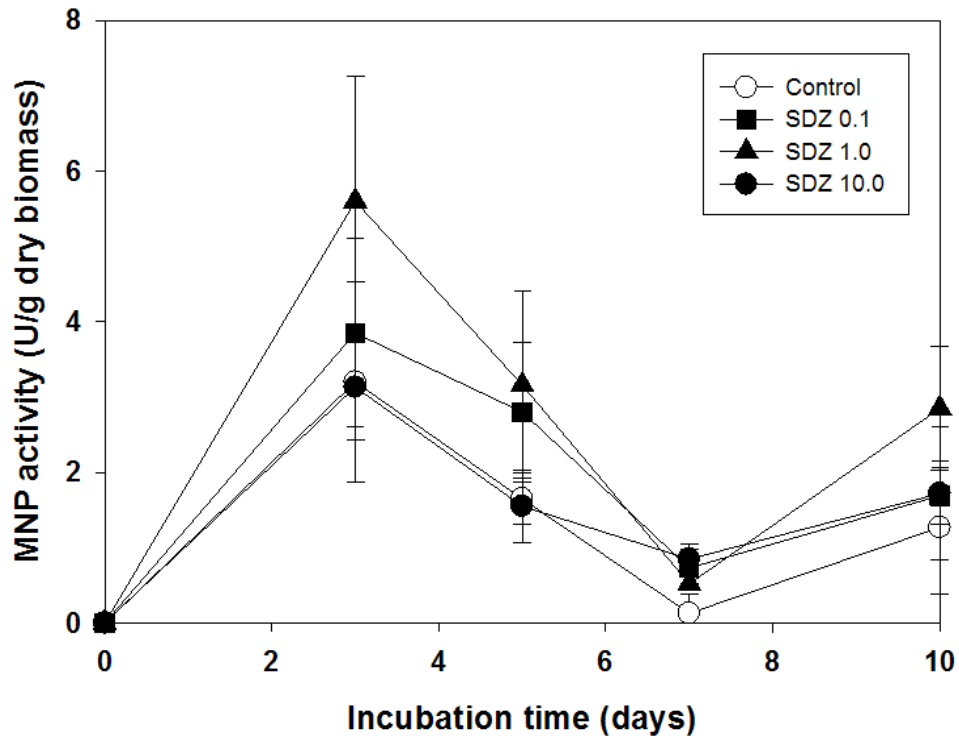


Fig 2. Effect of lincomycine (LIN) at various concentrations (mg/L) on (A) acid phosphatase (ACP) and on (B) β -glucosidase (GLU) in liquid cultures of *T. versicolor*. Results are expressed as means \pm standard errors.

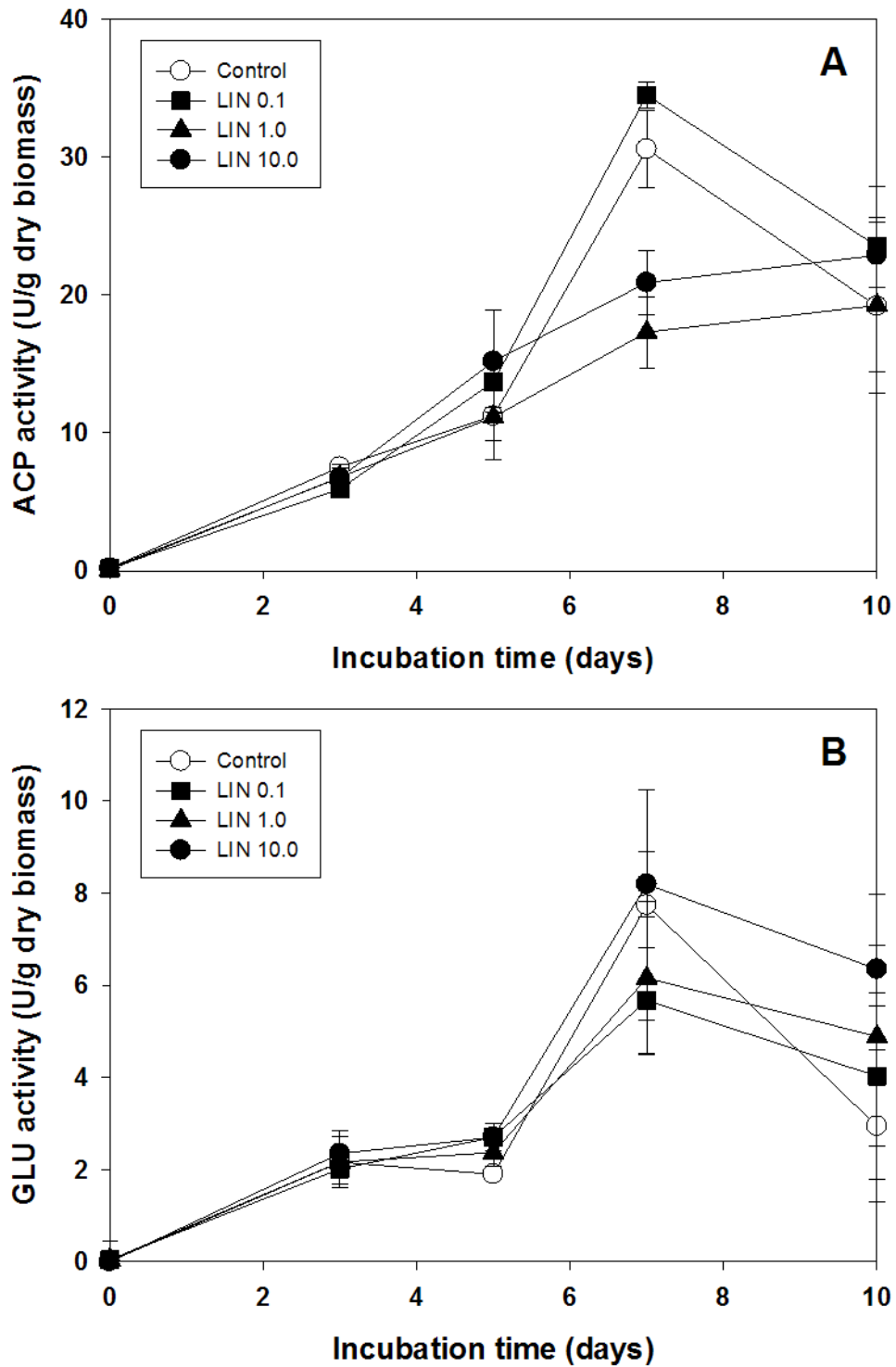


Fig 3. Evolution of β -glucosidase activity (GLU) in TMEs filled with green or slurry spiked with lincomycine (LIN) at two concentrations ($\mu\text{g}/\text{kg}$). Results are expressed as means \pm standard errors.

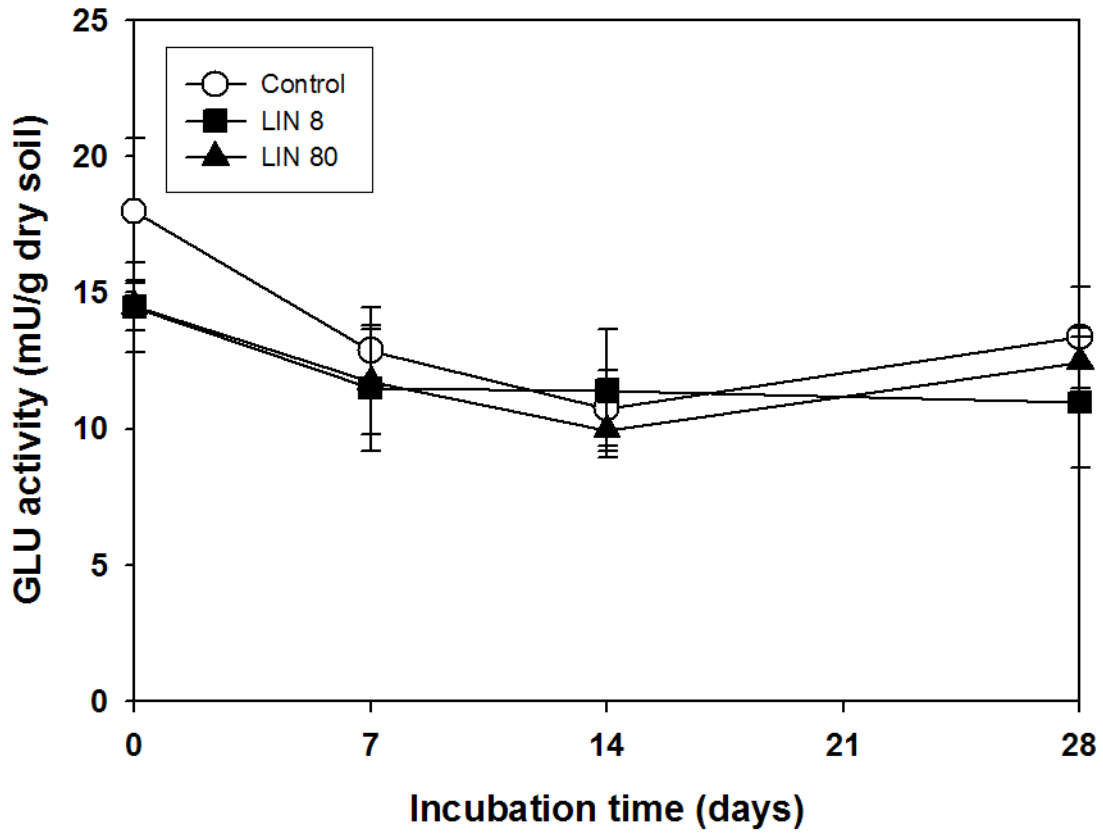


Figure 4: Evolution of dehydrogenase activity (DHA) in TMEs filled with green or slurry spiked with (A) lincomycine (LIN) at two concentrations ($\mu\text{g}/\text{kg}$) or (B) ciprofloxacin (CIP) at two concentrations (ng/kg). Results are expressed as means \pm standard errors.

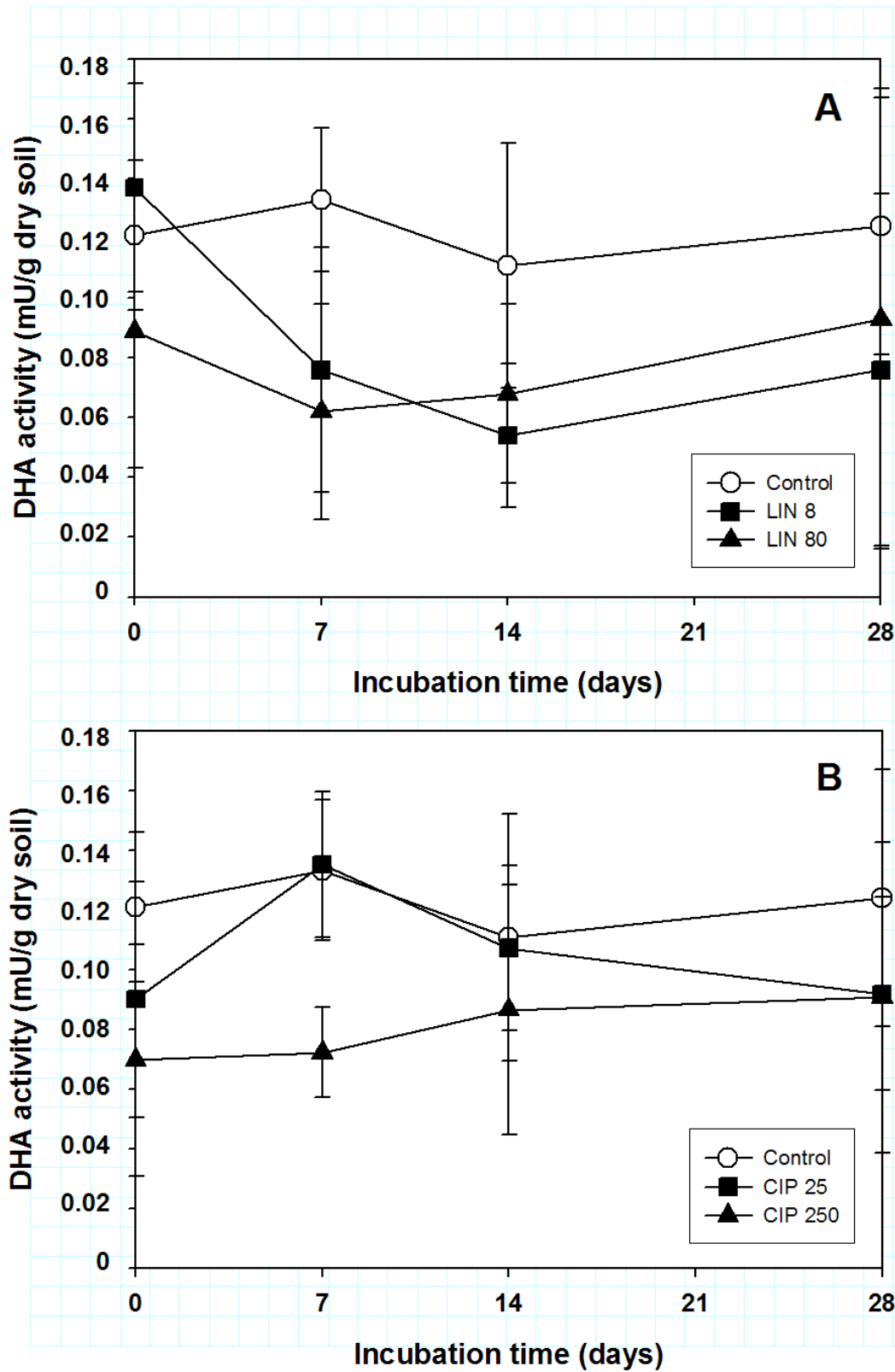


Figure 5: Evolution of bacterial biomass in TMEs filled with green or slurry spiked with (A) lincomycine (LIN) at two concentrations ($\mu\text{g}/\text{kg}$) or (B) ciprofloxacin (CIP) at two concentrations (ng/kg). Results are expressed as means \pm standard errors.

